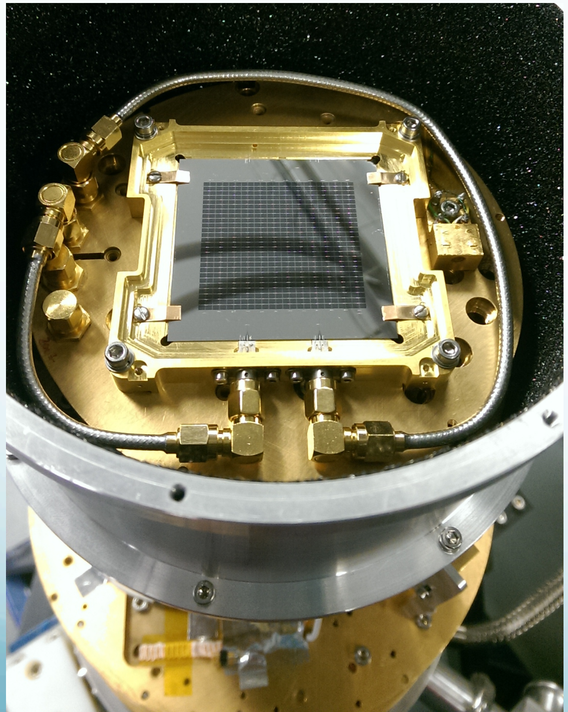
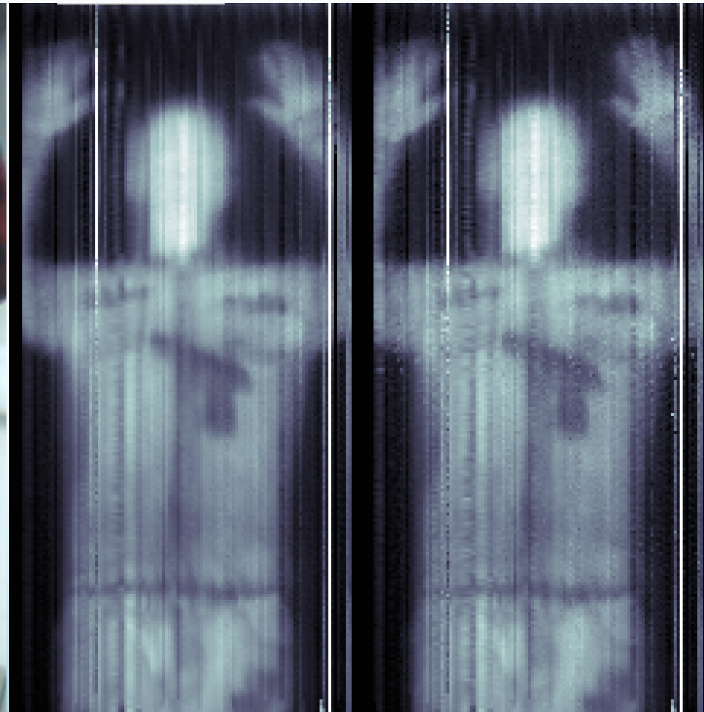
An Overview of Kinetic Inductance Detectors and Applications

Simon Doyle – Cardiff University



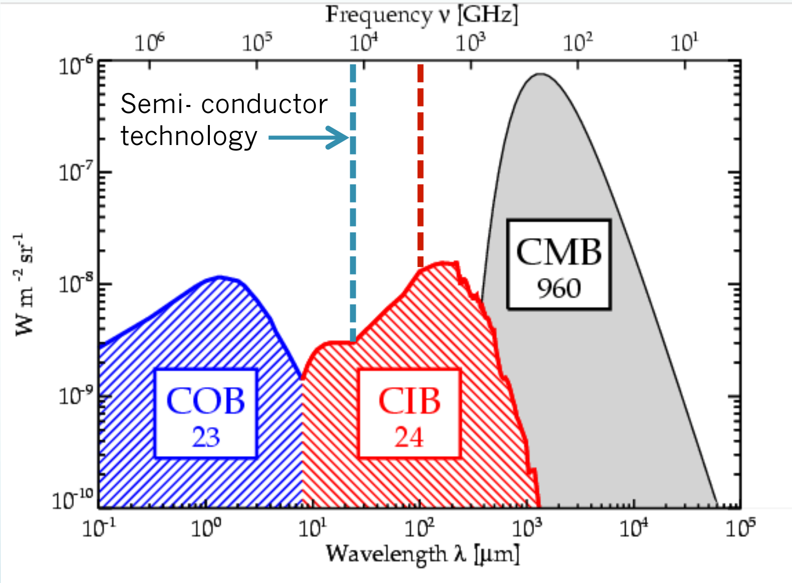


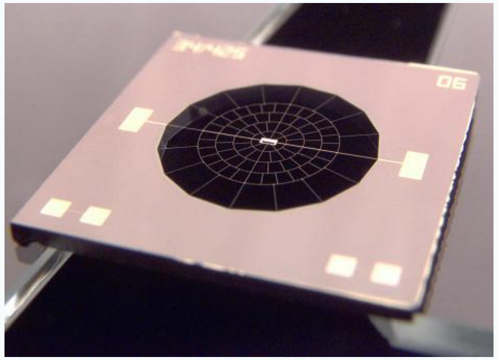
Talk Overview

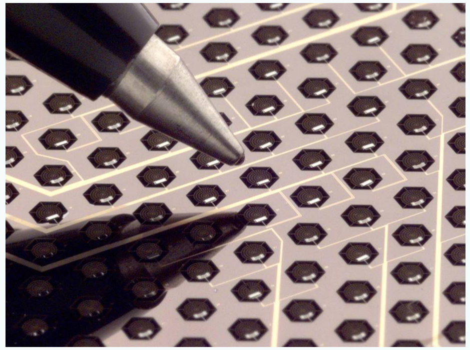
- Motivation for technology development
- Basic introduction to superconductor below the transition temperature
- The concept of Kinetic Inductance
- Basics description of superconductors at RF frequencies.
- Basic operating principal of a Kinetic Inductance Detector
- Resonator types and differences
- Multiplexed readout electronics
- Current and future KID based instruments

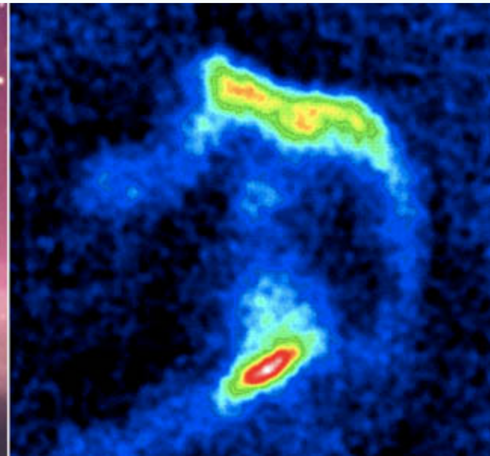
Motivation for detector development - Astronomy

- **Semi-conductor technology** Limited to wavelengths of order 200um (1.5 THz)
- **Heterodyne receivers** are typically noisy and not practical for large format imaging arrays
- **Bolometers** have sensitivity but poor multiplexing ratios

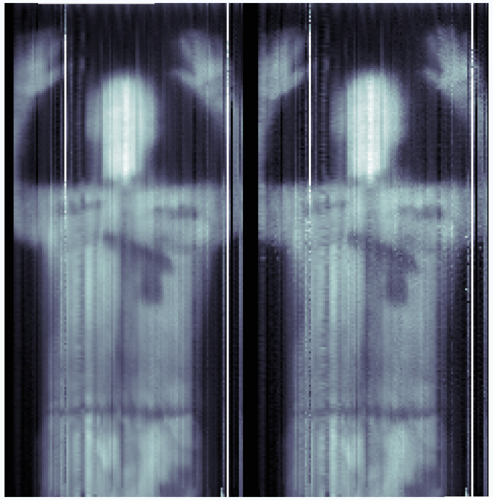


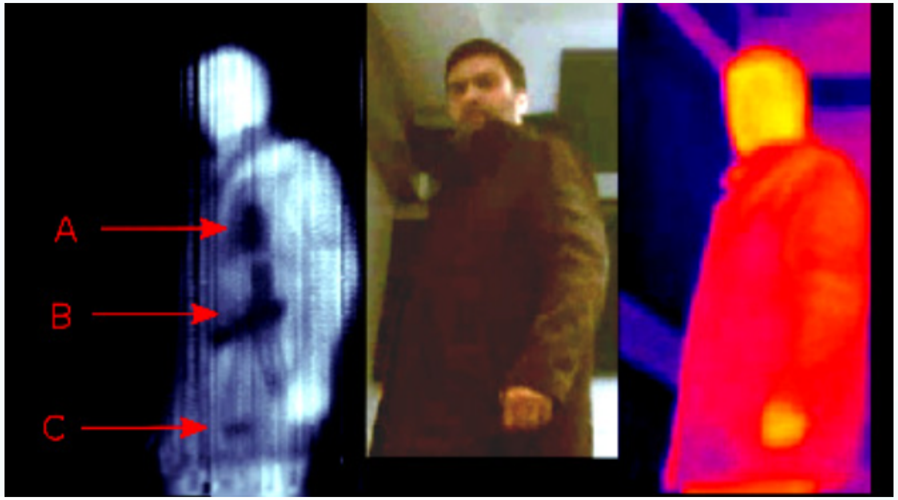


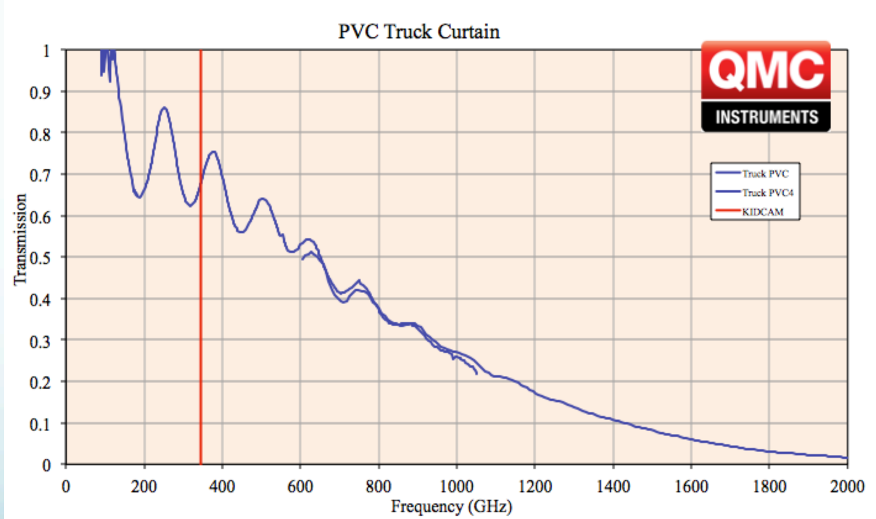




Motivation for detector development – Security and Industry







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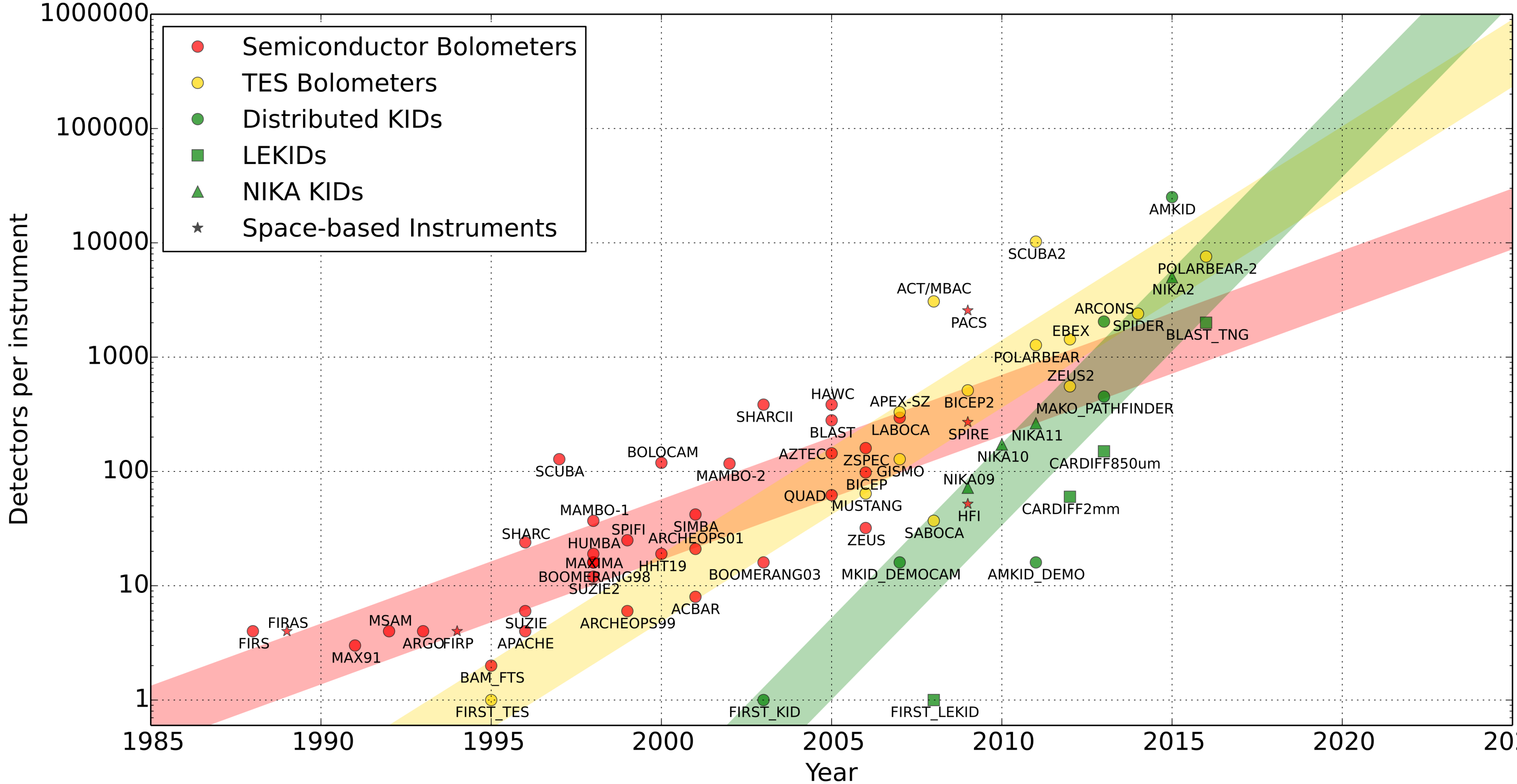
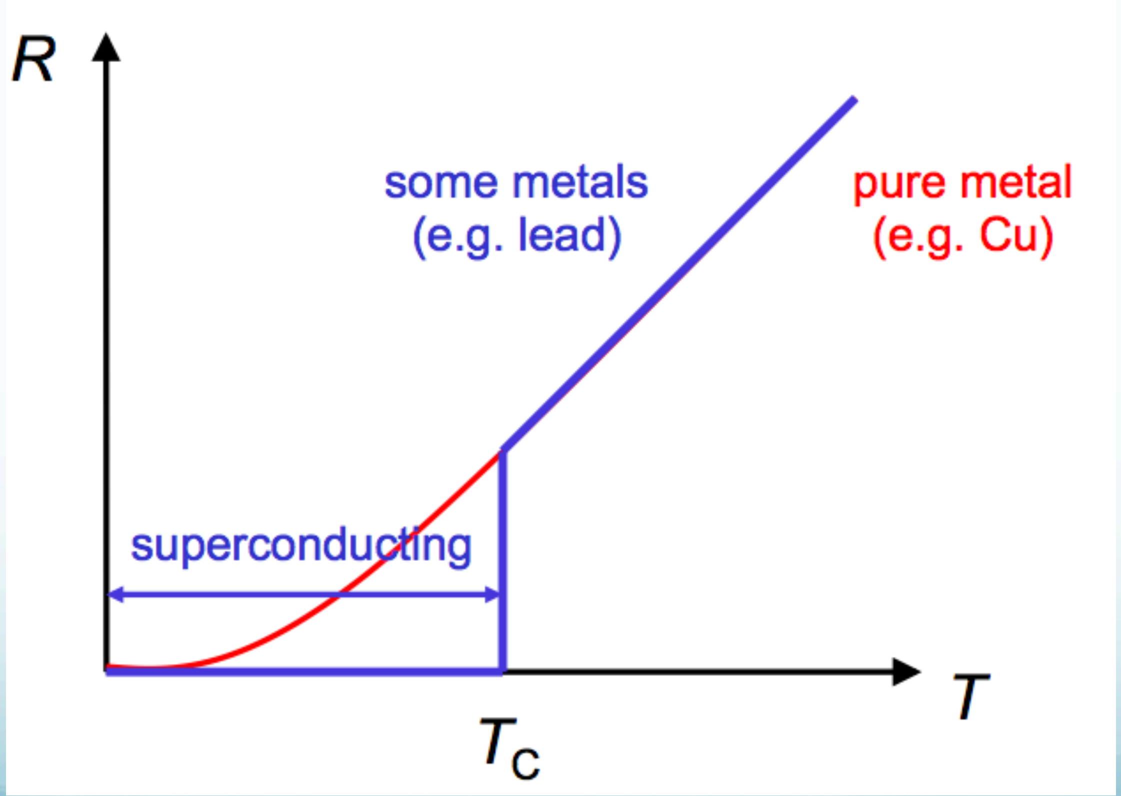
Motivation for detector development - Astronomy

Pixel counts in Astronomical receivers over the years



Basic Principals of a Superconductor

- Superconductors are most famous for demonstrating zero **DC** resistance at temperatures below the transition temperature (T_C)
- It would seem that the Physical properties of the superconductor is not changing below T_c. However ……..



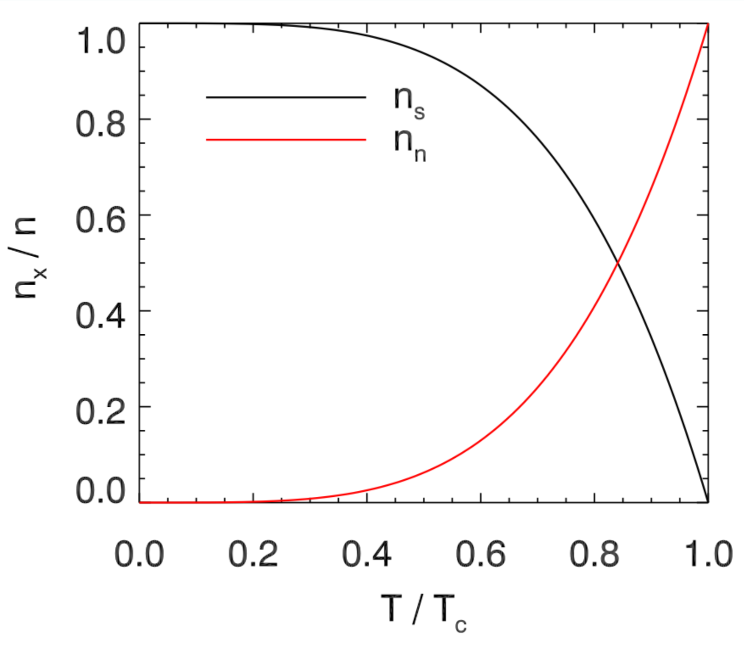
Below The Transition Temperature

Below T_c the electron population is dividing into separate populations.

A population of electrons weakly bound together called Copper pairs, bound together with an energy 2Δ (typically 0.4 meV) and denoted as n_s.

The remaining normal state electrons denoted n_n or n_{qp}

The populations can be described to first order by - $\frac{n_s}{n} = 1 - \left(\frac{T}{T_c}\right)^4$



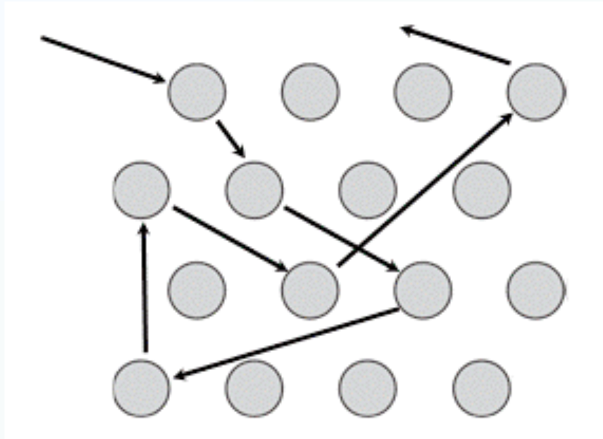
$$n_{qp} = n - n_s$$

n_n Behave as normal state electrons.

n_s Are paired electrons bound by and Energy 2Δ**. These paired electrons are immune from scattering and hence loss**

The conductivity of normal metals (Drude model)

$$\sigma_n = \frac{\sigma_0}{1 - j\omega t}$$



$$\sigma_n = \frac{n_n e^2 \tau}{m(1+\omega^2\tau^2)} - j\frac{n_n e^2 \omega \tau^2}{m(1+\omega^2\tau^2)}$$

$m = 9.1x10^{-31}$
$n_n \approx 10^{29}$

τ is typically of order 10^{-14} s and at practical frequencies, say f=5GHz ($\omega=3x10^{10}$) leaving $\omega^2\tau^2 << 1$ and the imaginary term negligible.

$$\sigma_n = \frac{n_n e^2 \tau}{m(1+\omega^2\tau^2)} - j\frac{n_n e^2 \omega \tau^2}{m(1+\omega^2\tau^2)} \rightarrow \sigma_n = \frac{n_n e^2 \tau}{m}$$

Conductivity of non-scattering electrons

The phenomena of superconductivity arises from the non-scattering properties of the superconducting electron population n_s.

Consider the Drude model where $\tau \rightarrow \infty$ to denote a non-scattering electron population n_s.

$$\sigma_s = \frac{n_s e^2 \tau}{m(1+\omega^2\tau^2)} - j\frac{n_s e^2 \omega \tau^2}{m(1+\omega^2\tau^2)}$$

$$\sigma_1 = \frac{n_s e^2}{\frac{m}{\tau} + m\omega^2\tau} \xrightarrow{\tau\to\infty} 0$$

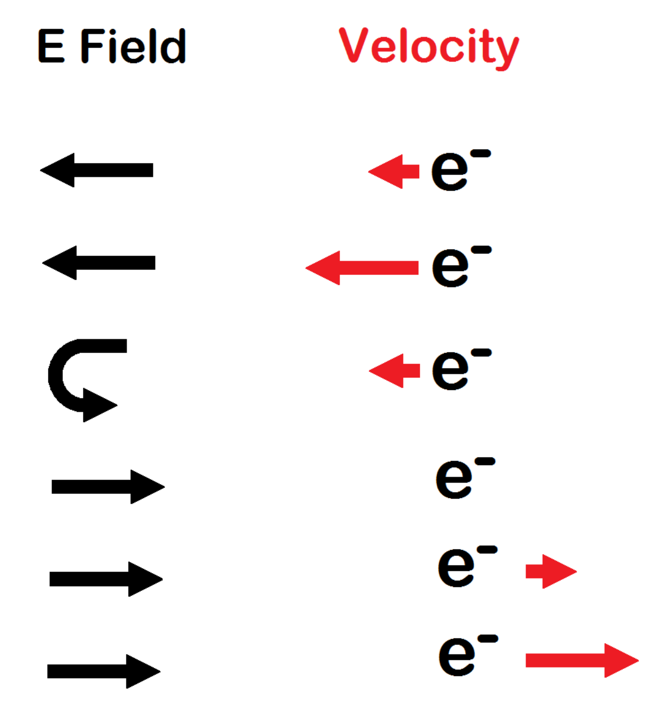
$$\sigma_2 = -j\frac{n_s e^2 \omega}{\frac{m}{\tau^2} + m\omega^2} \xrightarrow{\tau\to\infty} -j\frac{n_s e^2}{m\omega}$$

$$\sigma_2 = -\mathbf{j}\frac{n_s e^2}{\omega m}$$

What is Kinetic Inductance?

- A complex surface impedance associated with the inertia of a non-scattering electron population in a superconductor (Cooper-pairs).

$$\sigma_2 = -\mathrm{j}\frac{n_s e^2}{\omega m}$$



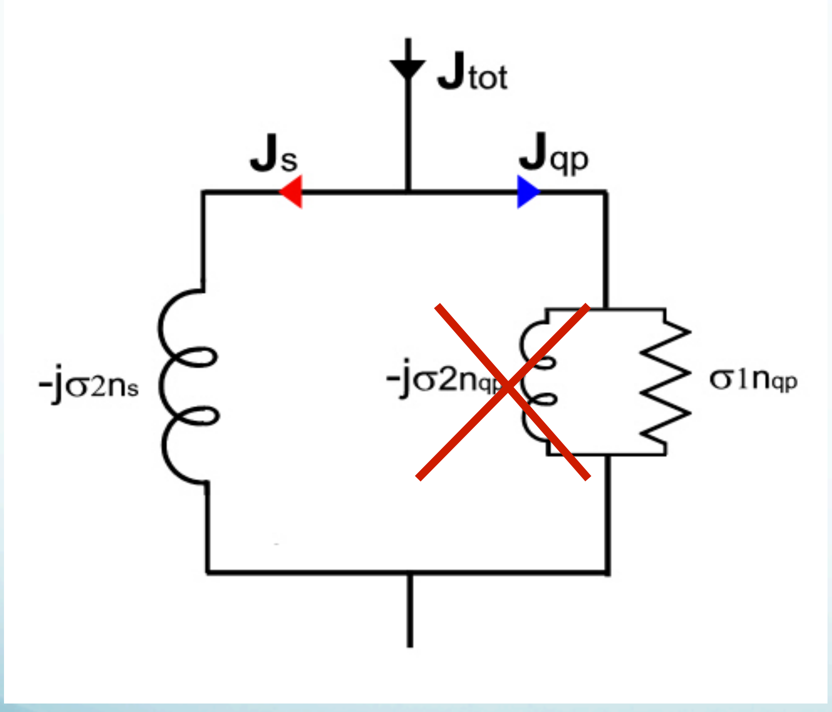
As an electron is accelerated in an electric field it gains kinetic energy due to the velocity gained and the electron mass.

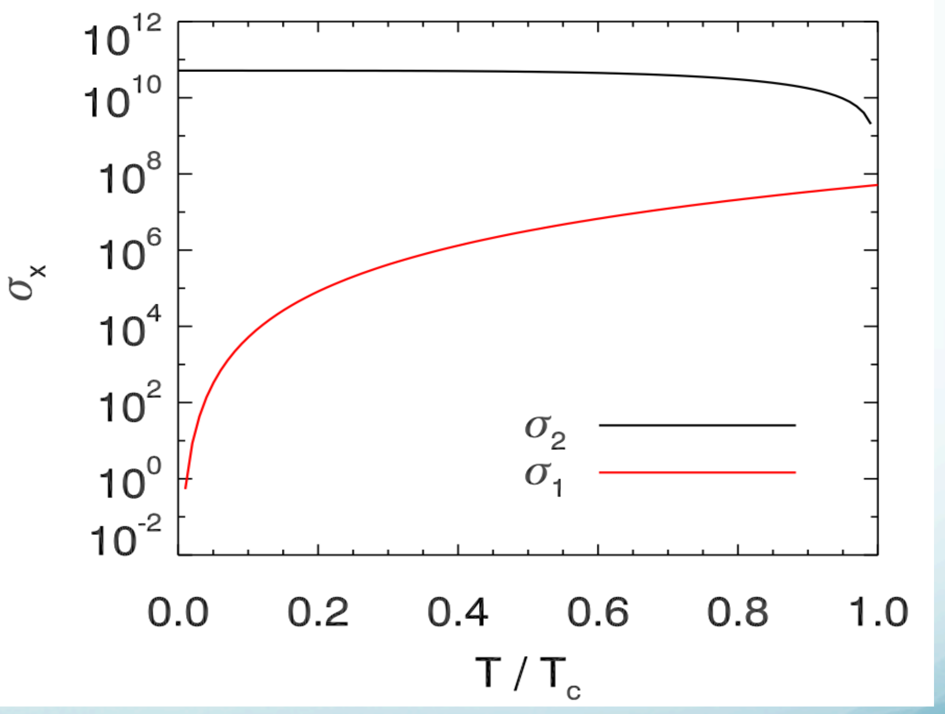
$$KE = \frac{1}{2} m_e V^2$$

When the field is reversed the kinetic energy gained must be returned to the field before the electron can change direction. The electron velocity is proportional to the current, hence the current will lag the field as it would in an inductor.

The two fluid model of superconductors

- The resistive behavior of a superconductor at RF frequencies can be explained by considering the two fluid model.





Quasi-particle lifetime

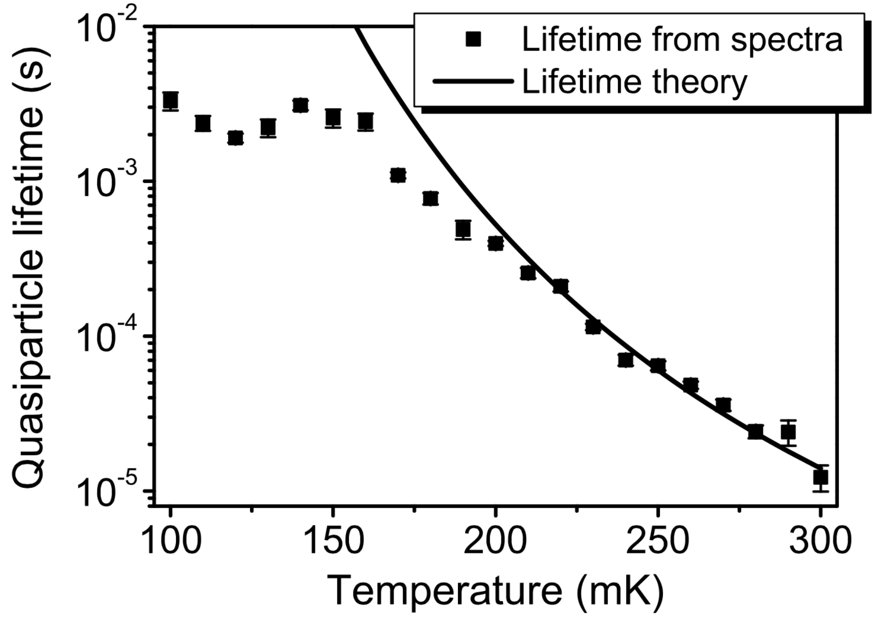
A Cooper pair can be split, by say absorbing a photon of energy hf>2Δ. The time for the quasi-particle to recombine to form a Cooper pair is dictated by the quasi-particle lifetime given by Kaplan theory:

$$\frac{1}{\tau_{qp}} = \frac{\sqrt{\pi}}{\tau_0}\left(\frac{2\Delta}{k_B T_c}\right)^{\frac{5}{2}}\left(\frac{T}{T_c}\right)^{\frac{1}{2}} e^{\frac{-\Delta}{k_B T}}$$

Metal	T_c/K	$\tau_0 \times 10^9 s$
Aluminium	1.19	438
Tantalum	4.48	1.78
Niobium	9.2	0.149
Tin	3.75	2.3
Zinc	0.875	780

Here τ_0 is a material dependent property

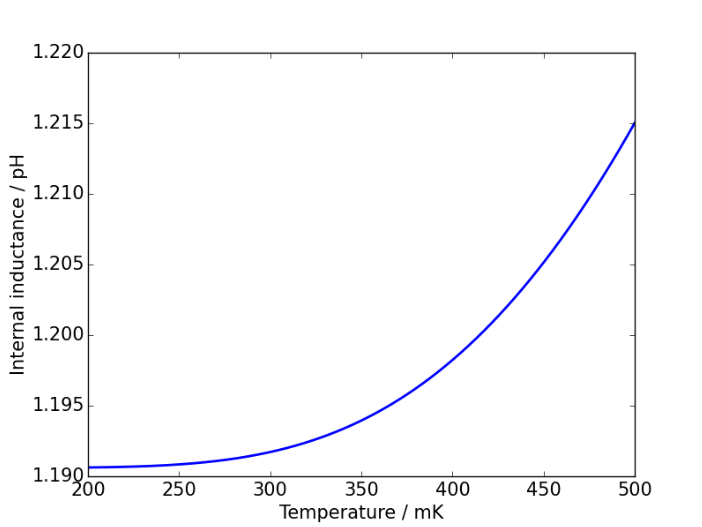
$$N_{qp} = \frac{P_{opt}\eta\tau_{qp}}{\Delta}$$

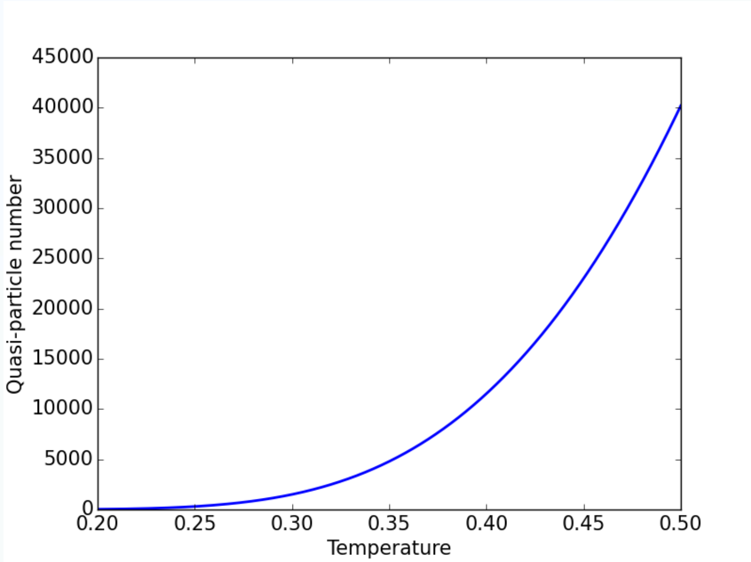


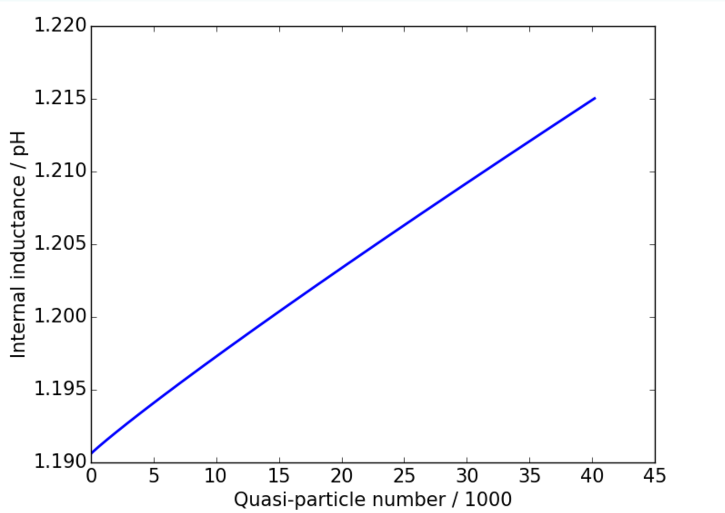
P.J. de Visser, et al., J. Low Temp. Phys., vol. 167, no. 3–4, pp. 335–340, Jan. 2012.

Response to change in quasi-particle density

30nm Al film 4x4μm patch simulated over 200-500mK







- **Change in L_{int} with temperature is small at T << TC**
- **Change in L_{int} with quasi-particle number typically of order 10^{-18} H/QP**

To recap

- Superconductor have two electron population
  - A normal state population giving a **conductivity** σ_1
  - A paired population that **does not scatter** giving a **conductivity** σ_2

- Photon absorption alters the populations **increasing** σ_1 and **reducing** σ_2.

- The number of quasi-particles generated for a given power is proportional to the **quasi-particle lifetime.**

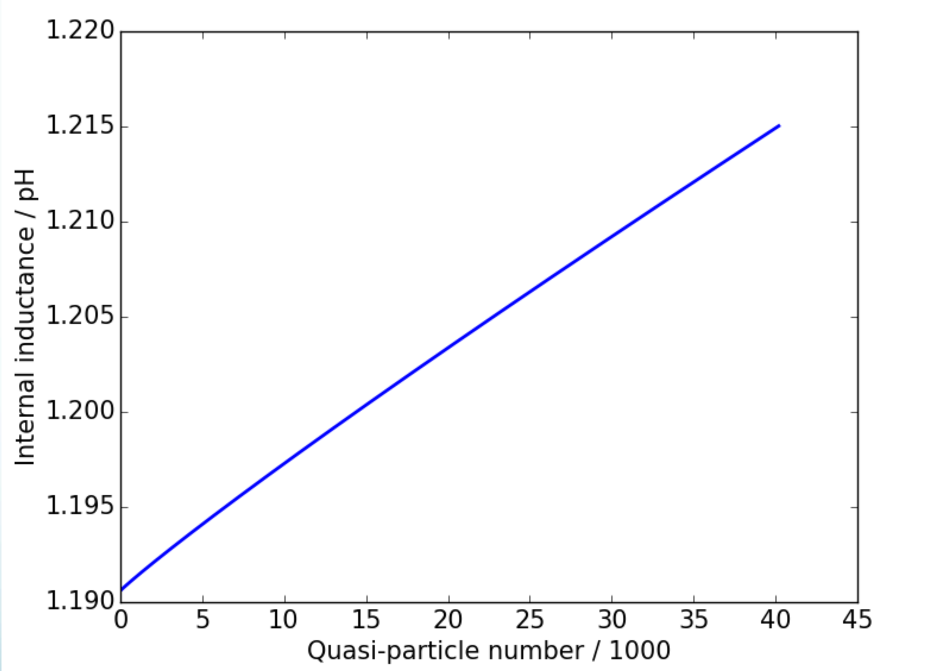
- **This is the basis of photon detection**

How to measure small changes in surface impedance

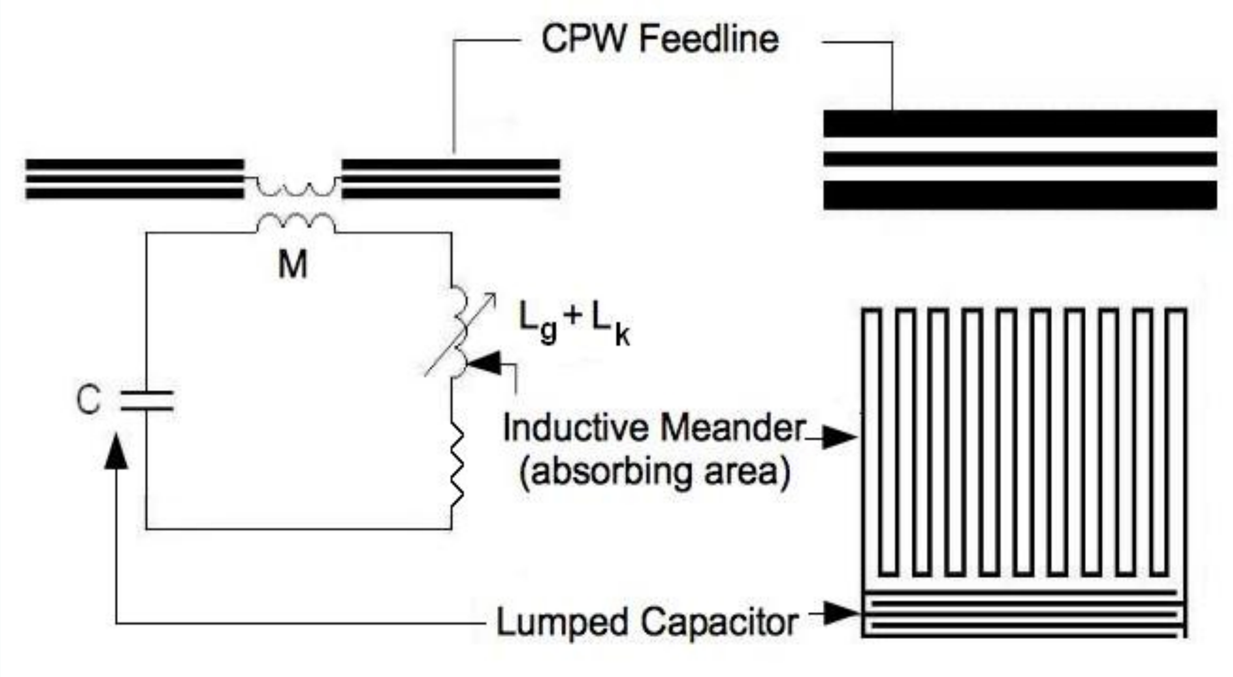
- Change in internal inductance is still relatively small for typical variations in source power

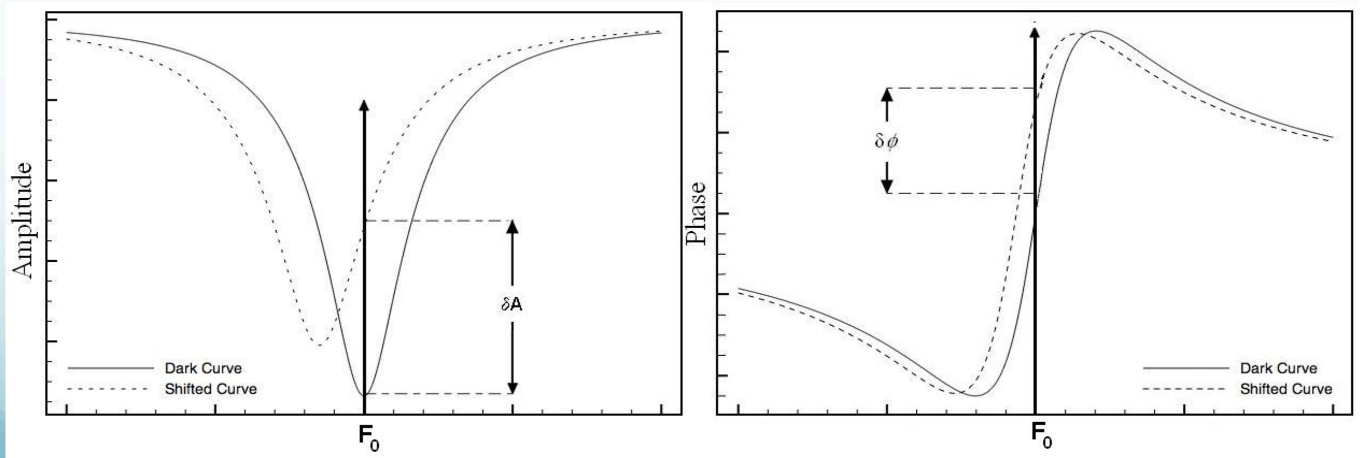
- This small change can be sensed using:

  - Hi Q microwave resonators
  - Low noise cryogenic amplifiers

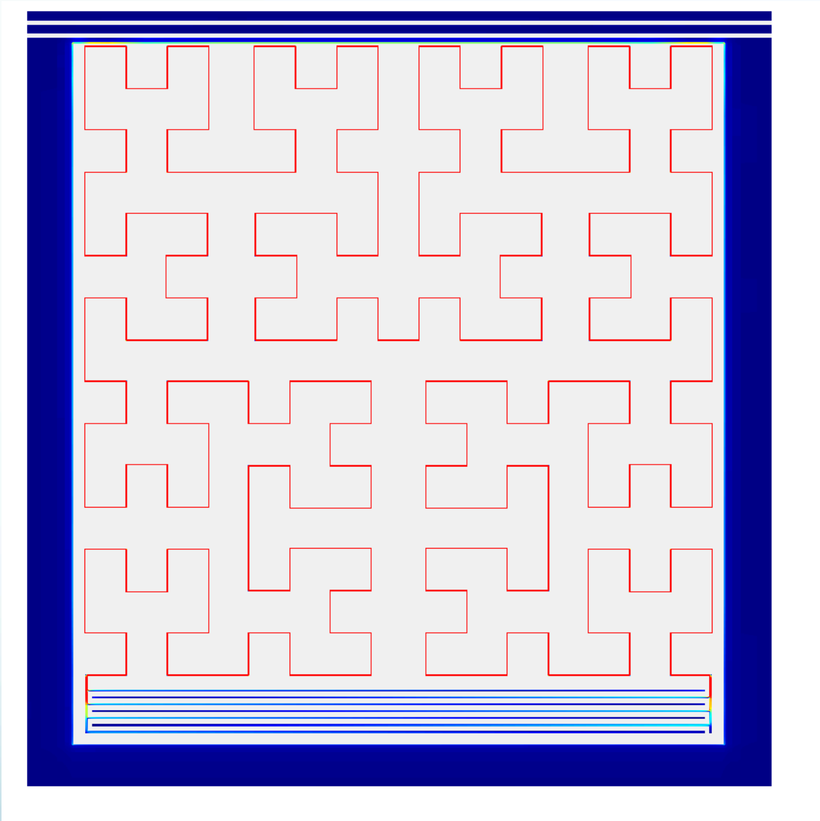


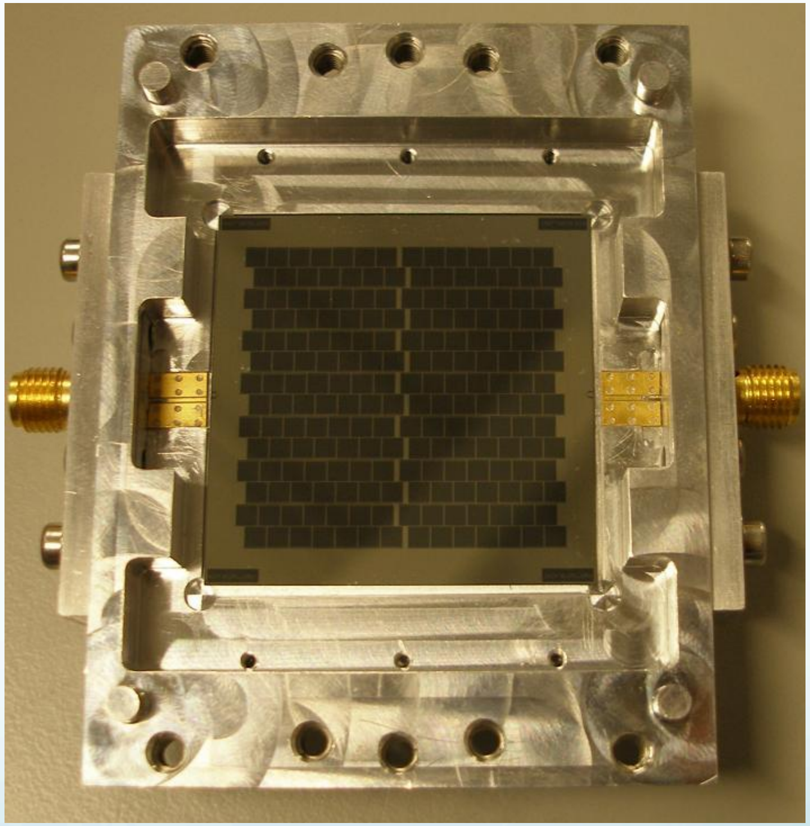
Basic principals of a Kinetic Inductance Detector



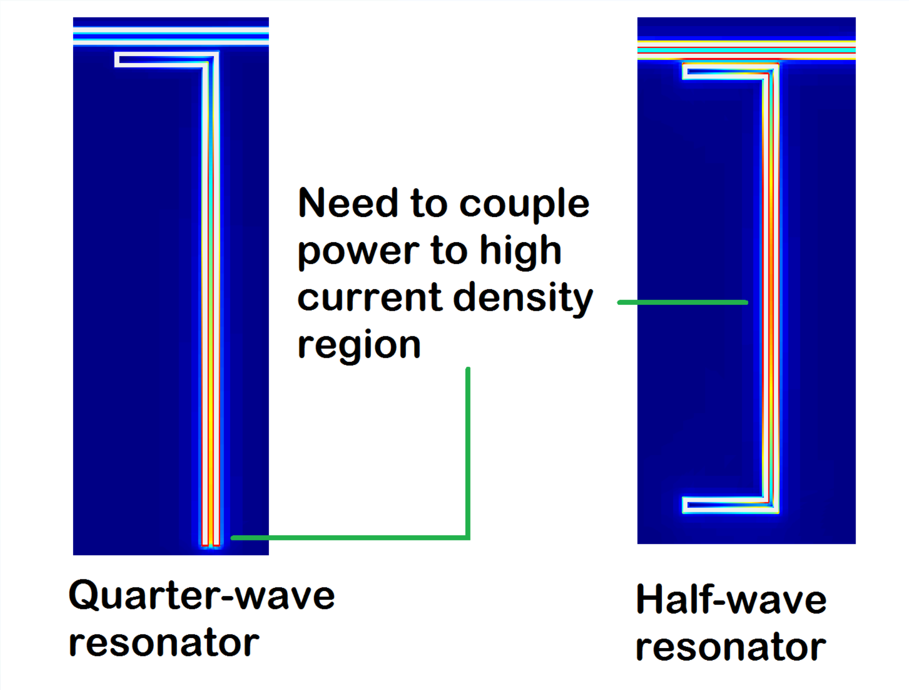


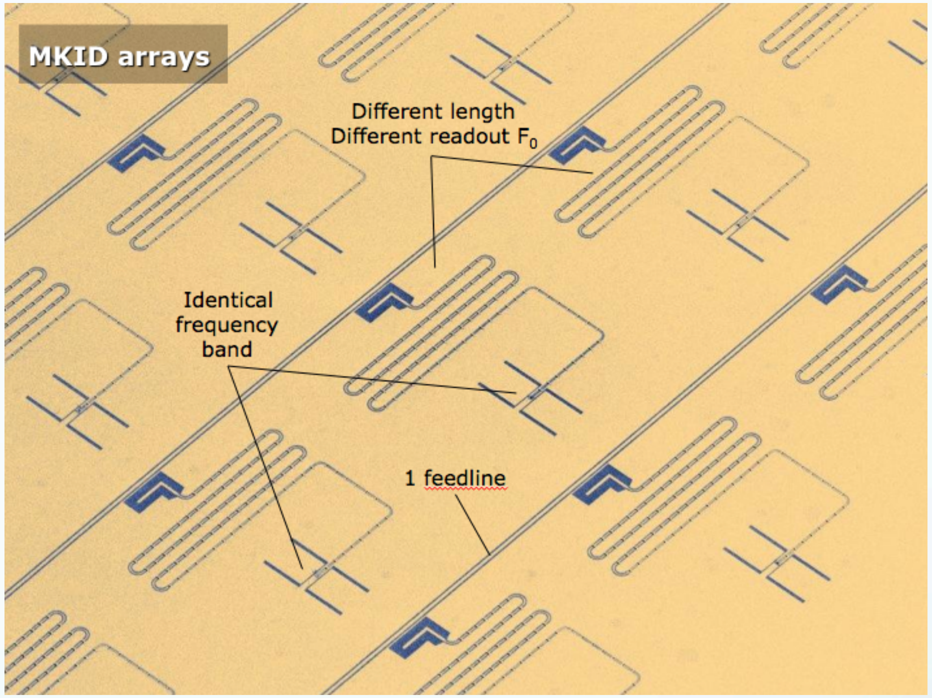
Types of KID detector – The Lumped Element Kinetic Inductance Detector (LEKID)





Types of KID detector – Distributed Kinetic Inductance Detector (MKID)





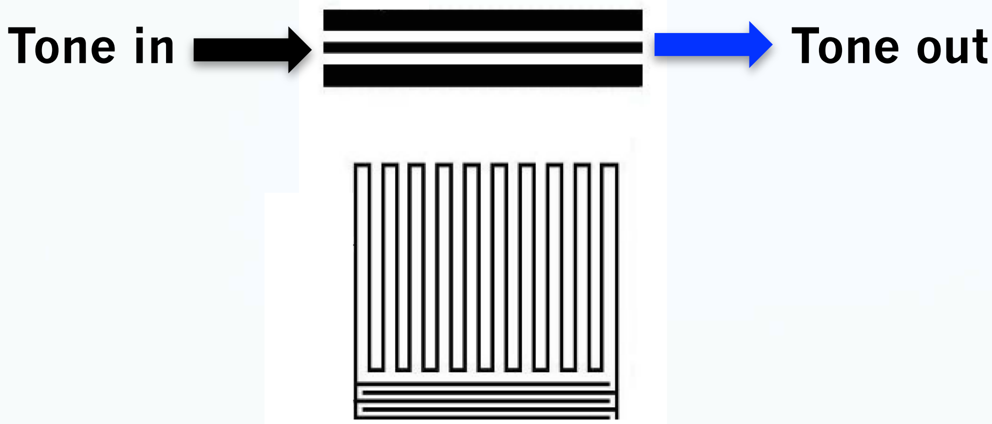
Measuring the sensitivity

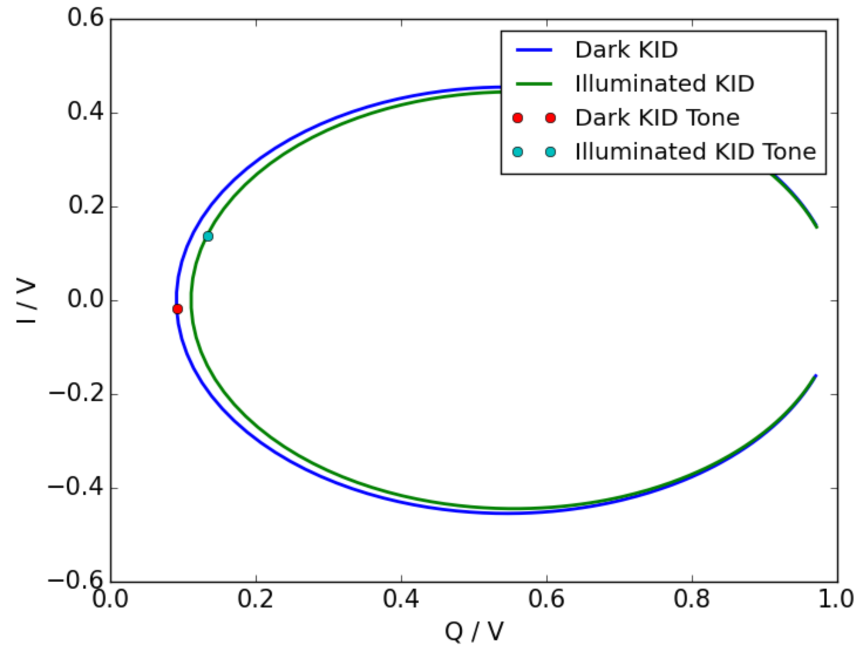
- The sensitivity of any detector is measured by:
  - Measuring the response to optical power – in the case of the KID dF_0/dP.
- The sensitivity then depends on how accurately you can measure this response. We define a time over which we average measurement of the response to be 0.5s.
  - For a KID we measure F_0 for 0.5s and establish an error in our measurement. This is the noise

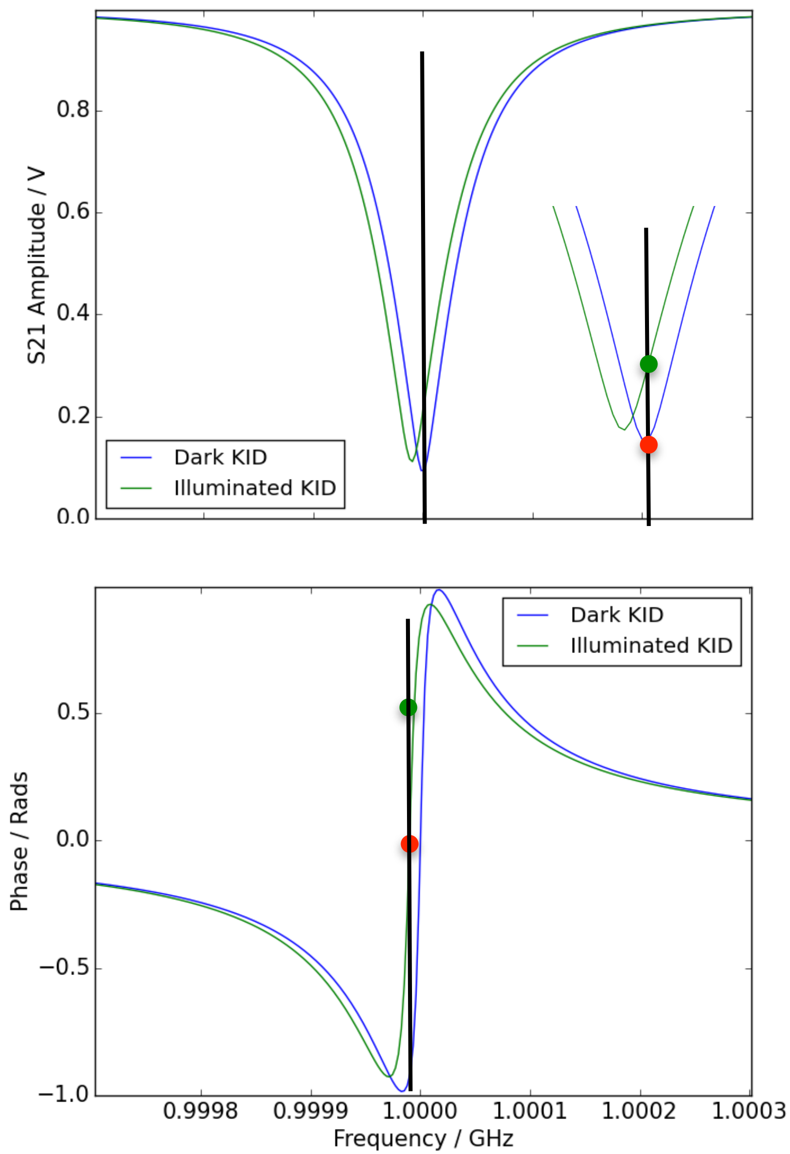
Measuring the sensitivity

- Noise occurs over a range of frequencies and forms a noise spectrum.
- In practice me measure this noise spectrum.
- This is done by measuring F_0 for a period of time and taking a Fourier transform.
- The resulting Fourier transform is scaled to give the noise in a 1 Hz bandwidth (0.5s) of integration as a function of frequency.

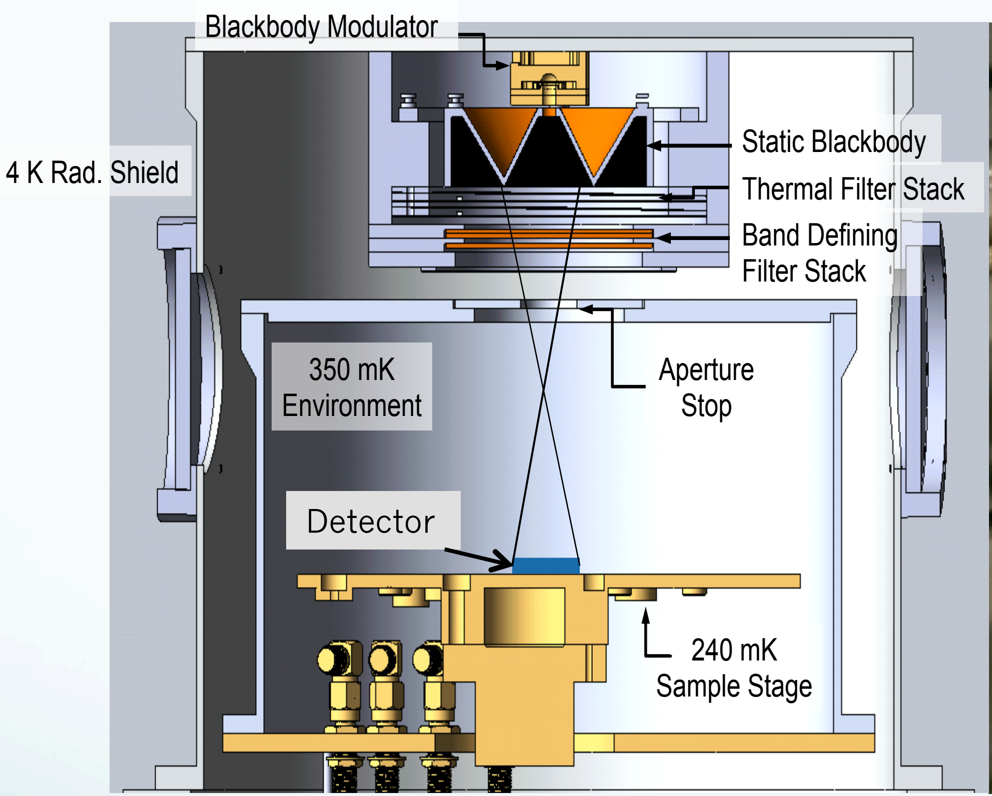
KID readout in the complex plane (IQ)

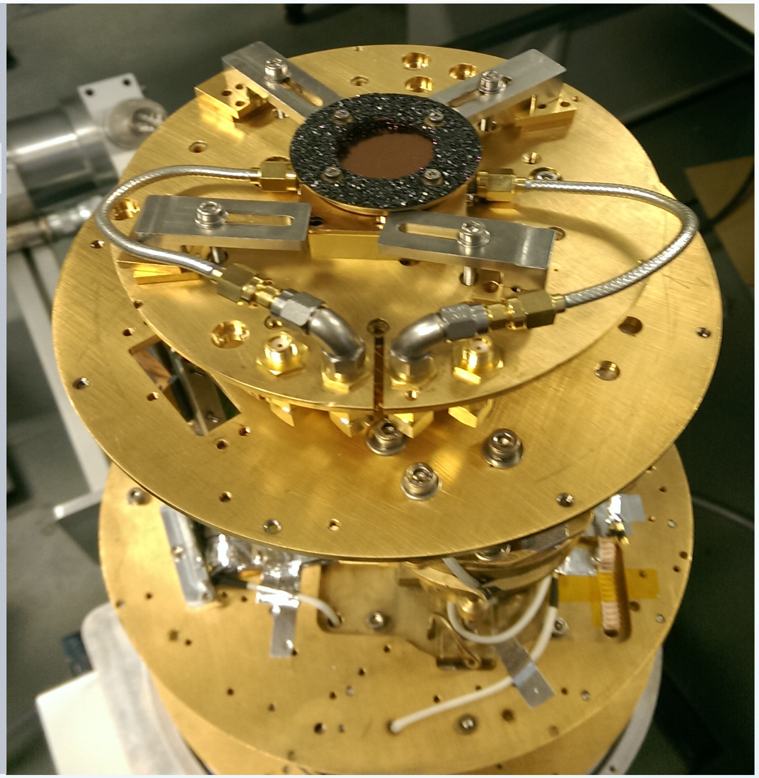




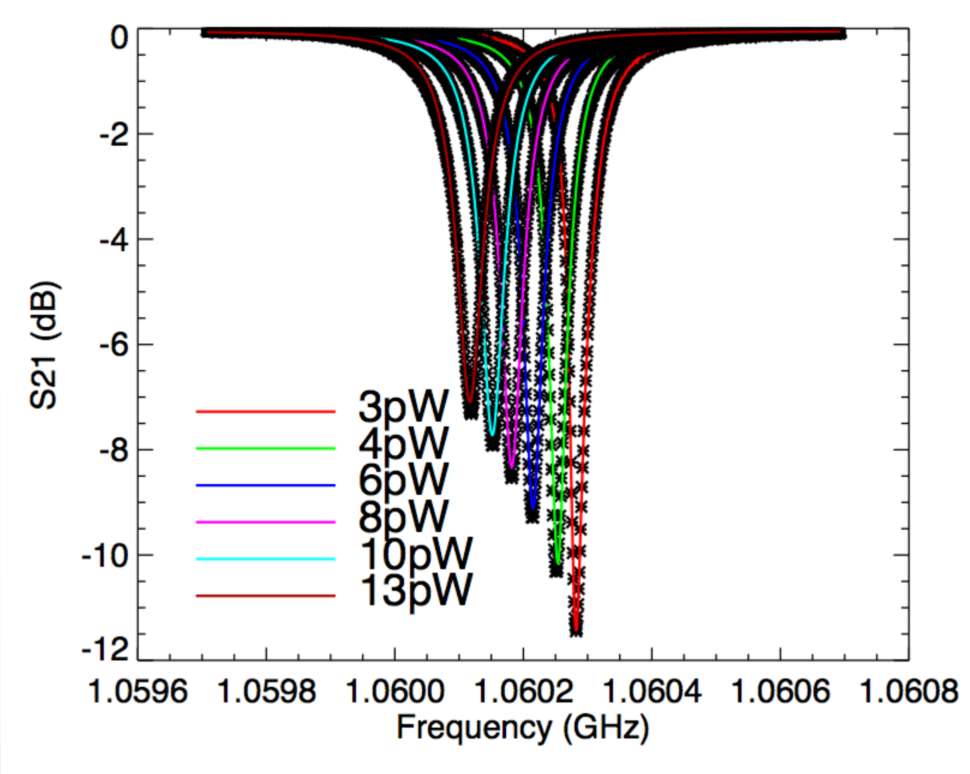


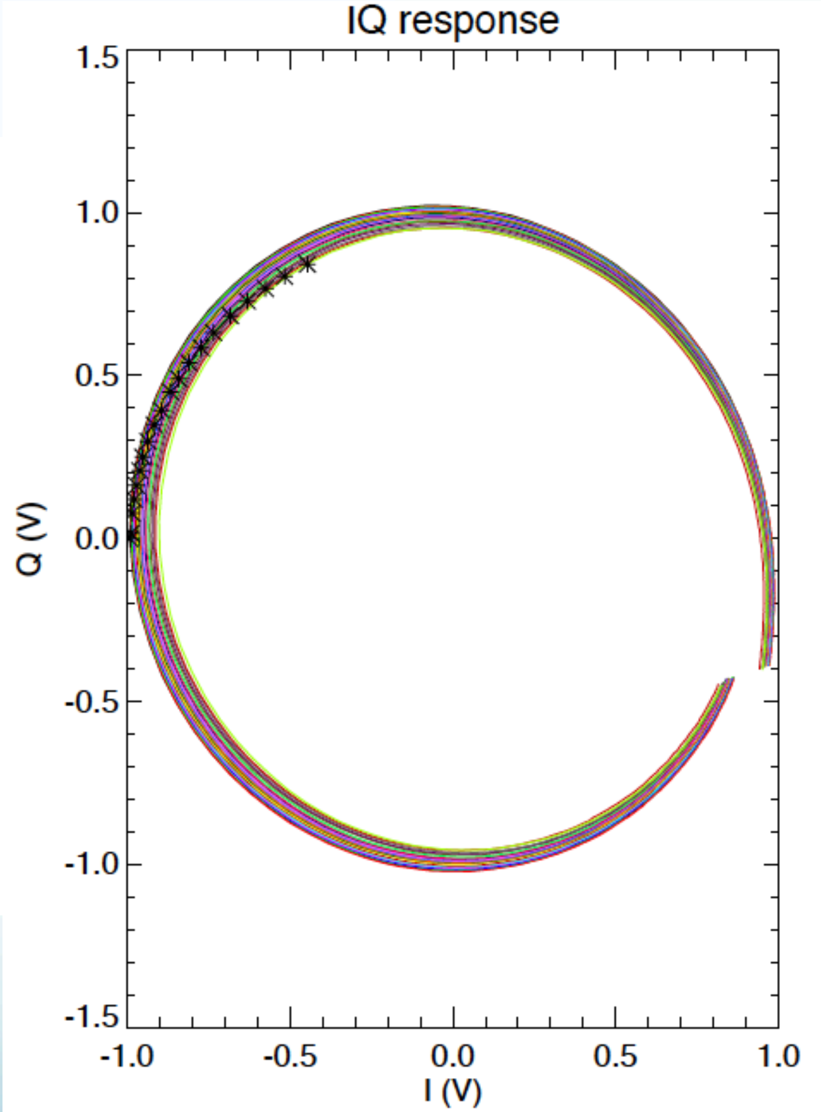
Measuring sensitivity





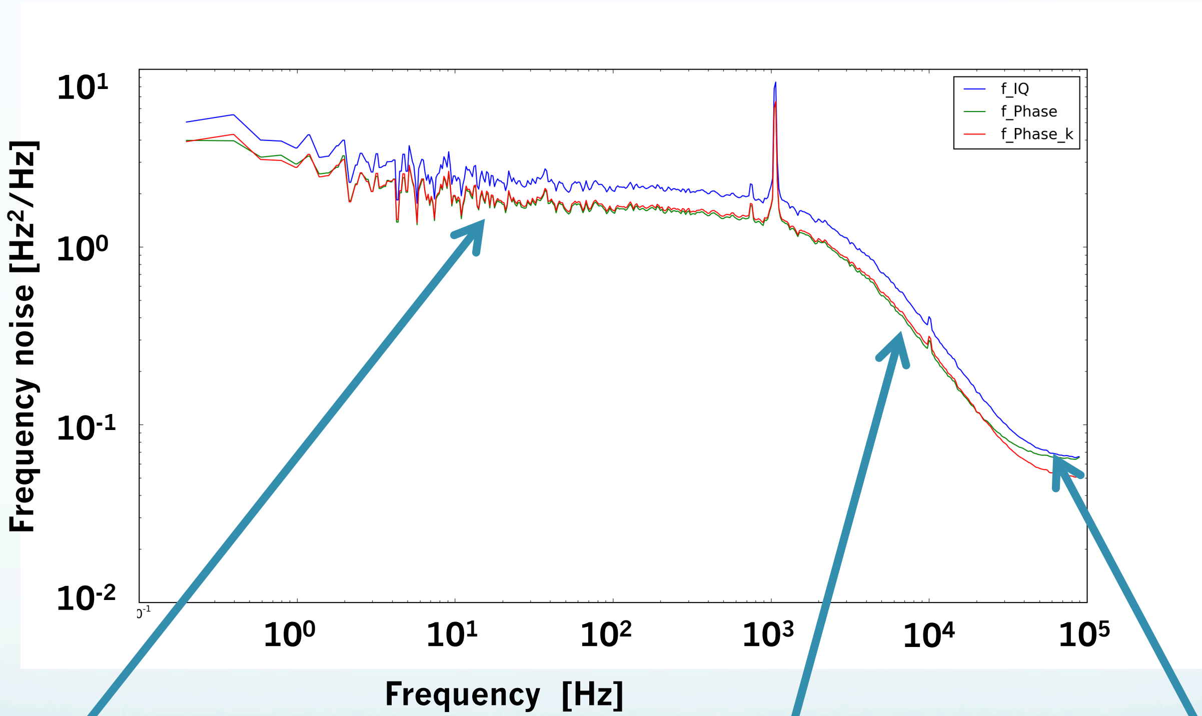
Response to photon absorption





Typical noise spectra of a KID

- **Generally clean noise spectra due to low susceptibility to EM noise sources.**



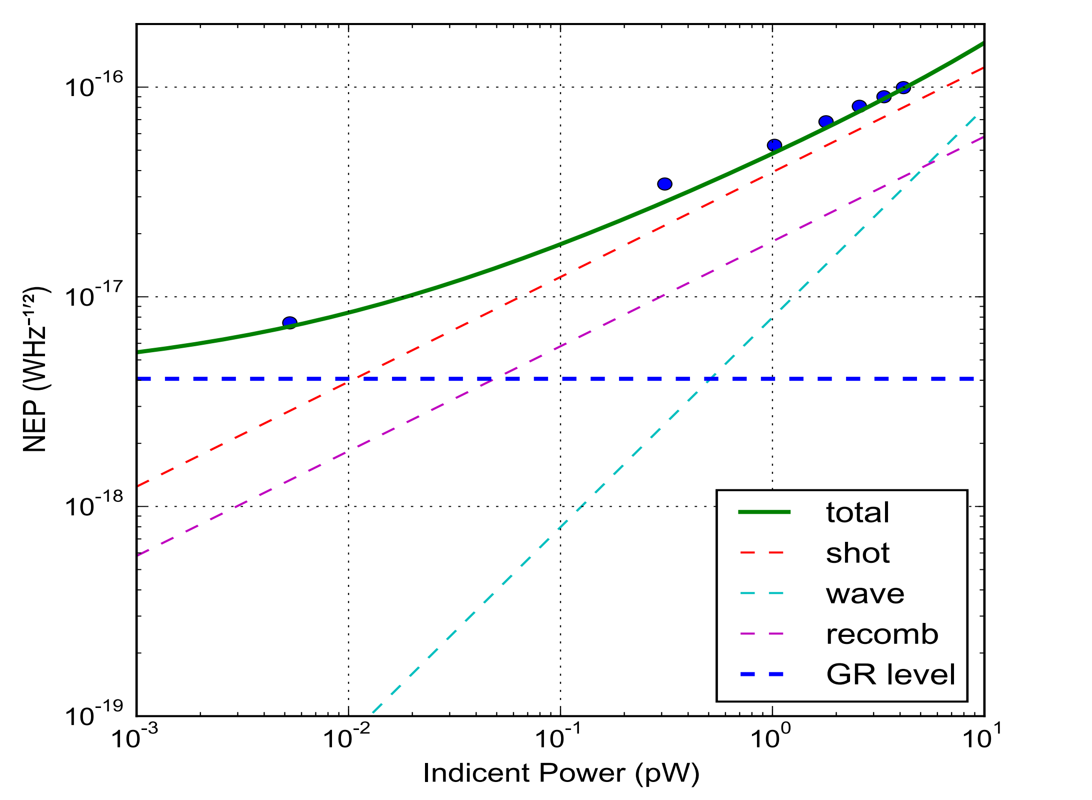
Inherent detector noise GR or Photon

Roll off due to Quasi-particle lifetime

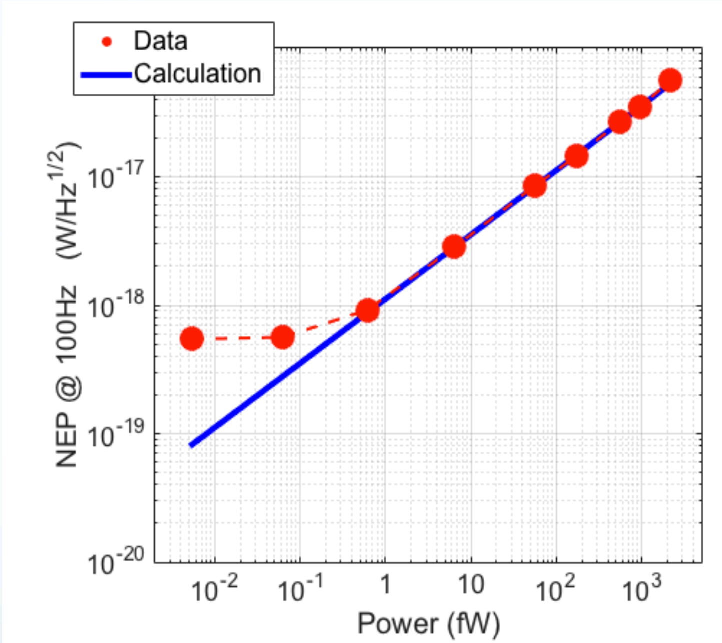
Amplifier noise floor

So we have a sensitive detector!

- KID detectors are extremely sensitive.
- Reach the photon noise limit down to powers of 1fW (10^{-15}W)
- This is the limit of any measurement imposed by the natural noise associated with the random arrival rate of photons from a source.



KID at 220mK



KID at 100mK better performance from cooling further

Putting NEP into context

- A 100W incandescent light bulb produces about 5W of optical power.
- If we placed our detector on a modest telescope with 1m^2 collecting area, how far away can our light bulb be an still be detected in 0.5 second of observing?
- NEP=$5\text{x}10^{-18}$ $\text{W/s}^{0.5}$ which means we have a signal to noise ratio of 1 if we observe for 0.5s. If we observe for 1 second this increases by $\sqrt{2} \approx 1.4$ - so just observable.

Flux at distance D from bulb

$$Flux = \frac{Power}{Area} = \frac{5}{4\pi r^2}$$

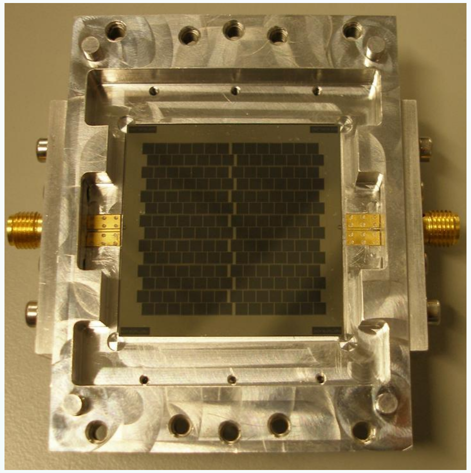
We collect over the 1m^2 area of the telescope so:

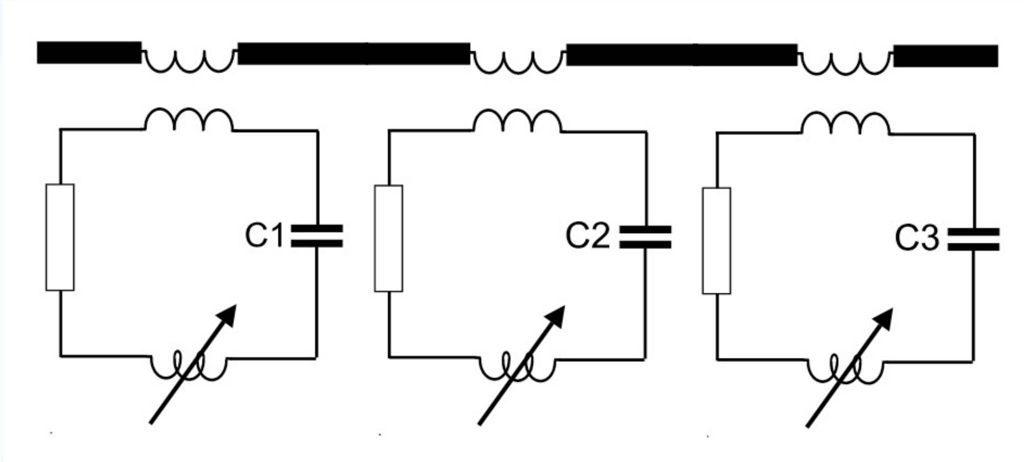
$$\frac{Power}{Area} \times \text{collecting area} = \frac{5}{4\pi r^2} \times 1 \rightarrow r = \sqrt{\frac{5}{4\pi \times Power}} = \sqrt{\frac{5}{4\pi \times 5 \times 10^{-18}}} = 2.8 \times 10^{8}\,\text{m}$$

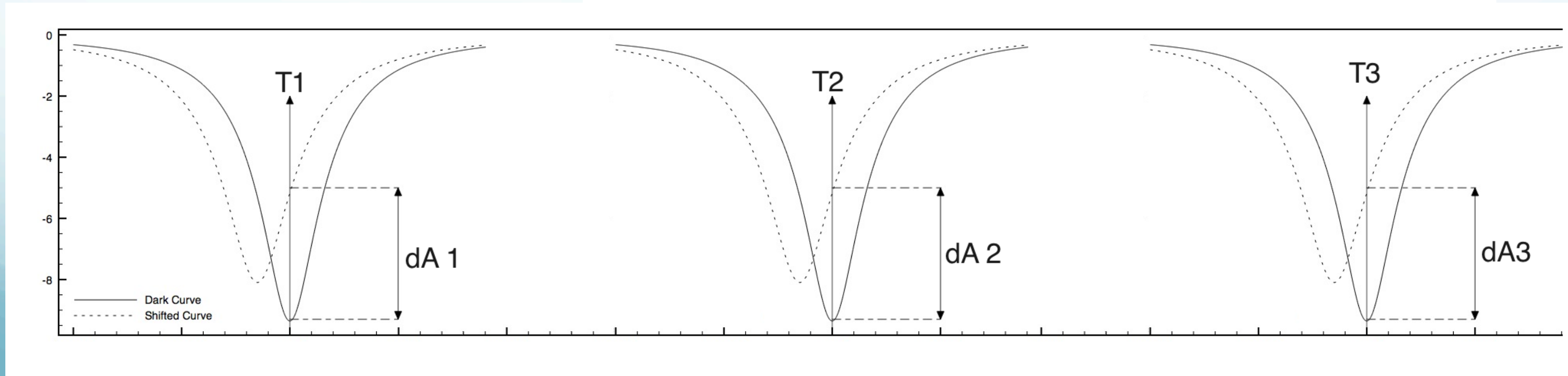
About 70% of the distance to the moon!

Natural multiplexing in KID devices

- Each LEKID is a high Q micro-resonator with a tunable f0
- We can therefore multiplex many LEKIDs onto a single CPW feed-line

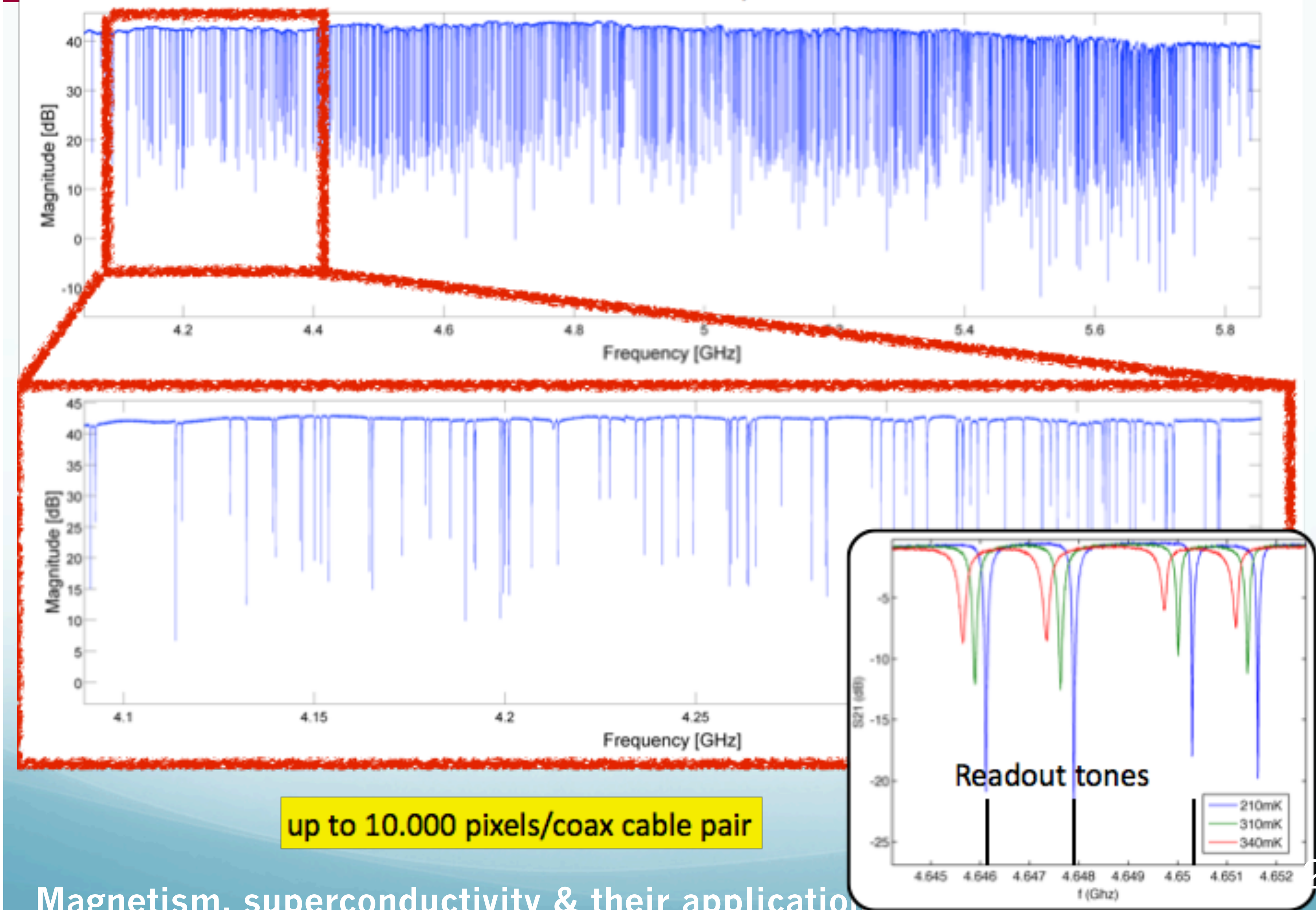






Principal of operation - Multiplexing

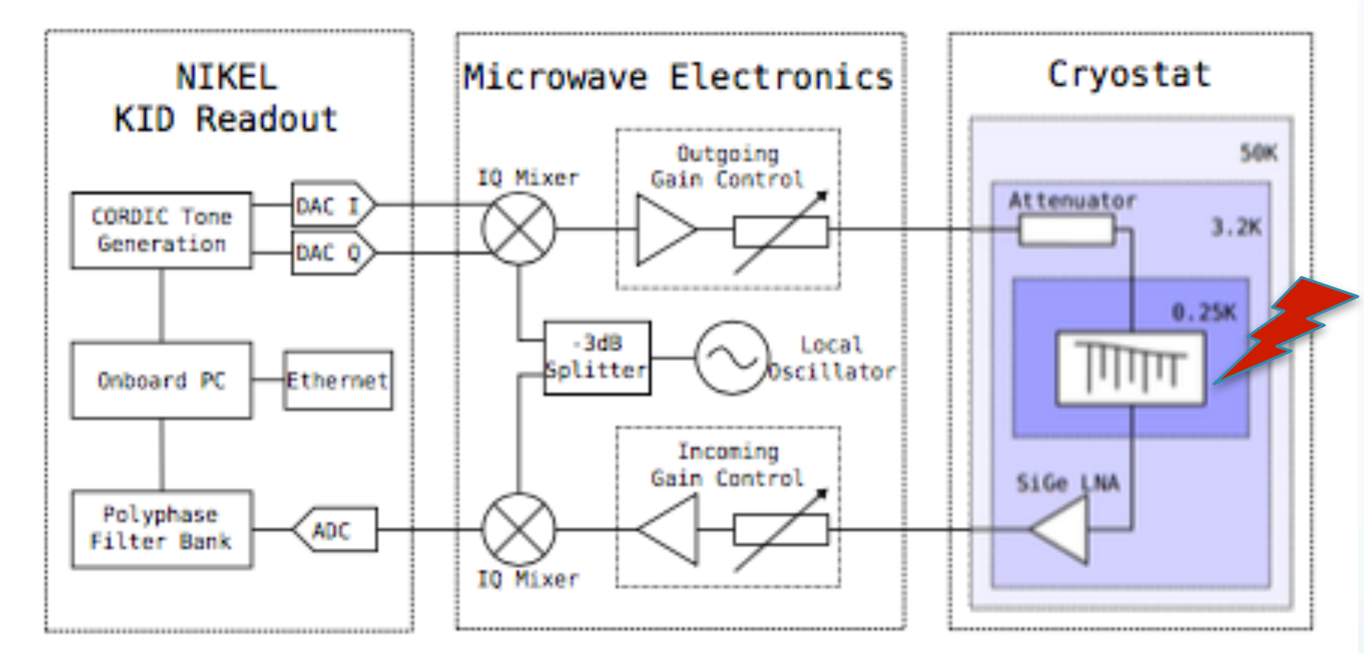
Readout: each dip = 1 KID



up to 10.000 pixels/coax cable pair

Simple Readout Electronics

Tone Generation **Mix up / Down** **Probe KID**

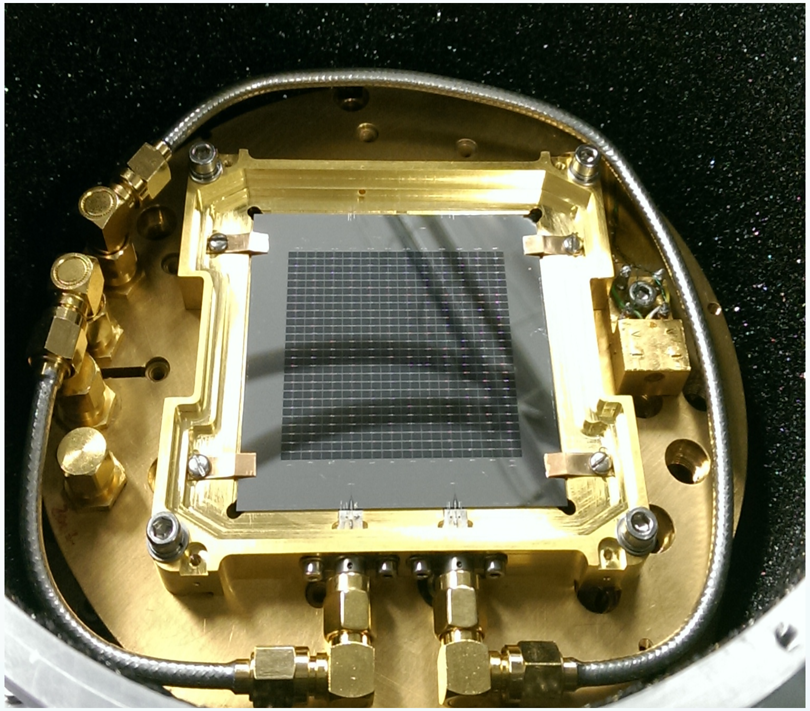


Light in through optics. E= hυ >2Δ

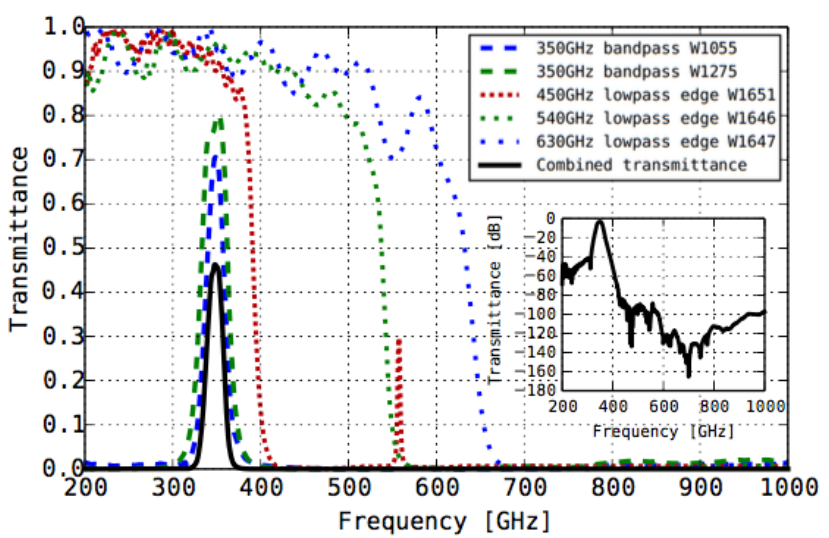
Warm **Cold**

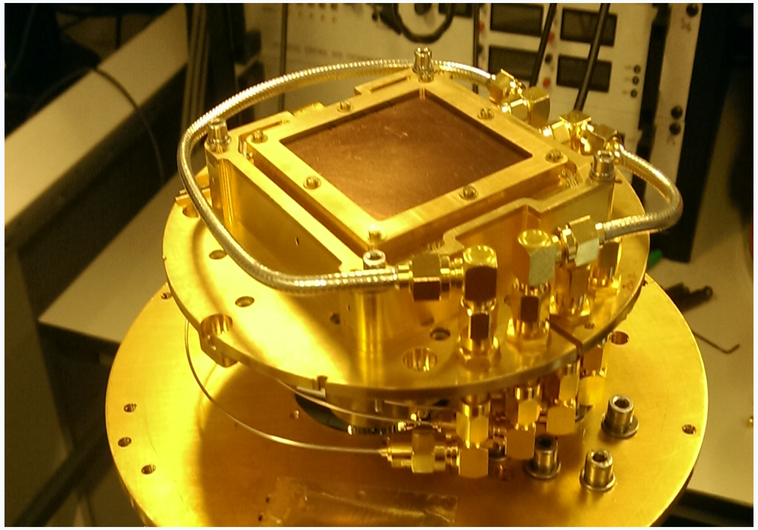
Making an array of LEKIDs

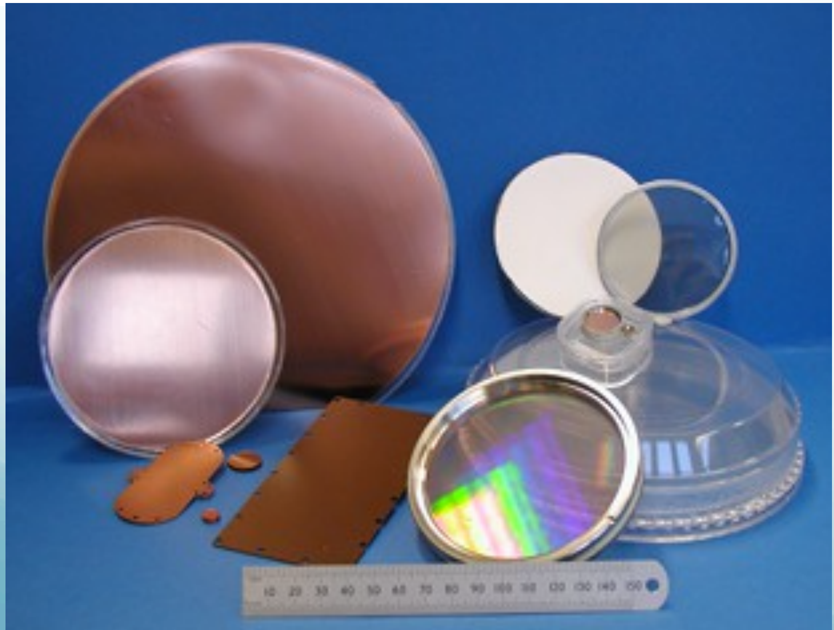
- In most cases 1 deposition and etch step
- Minimal material costs
- Cleanroom time ½ day



Optical coupling and band defining

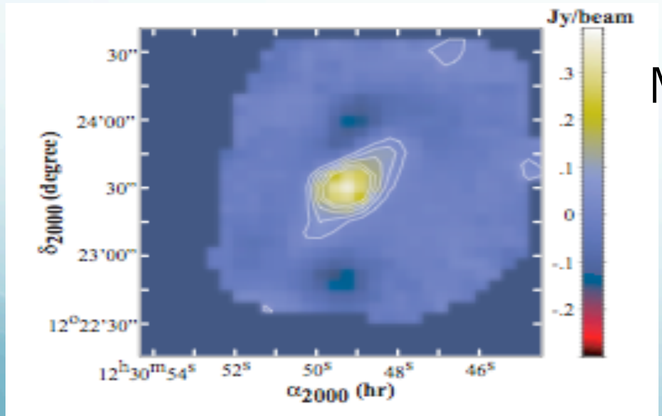






Current Instruments NIKA on IRAM

NIKA A dual band (150GHz and 220 GHz) mm astronomical camera on the IRAM telescope working just above the photon noise limit at 2mm



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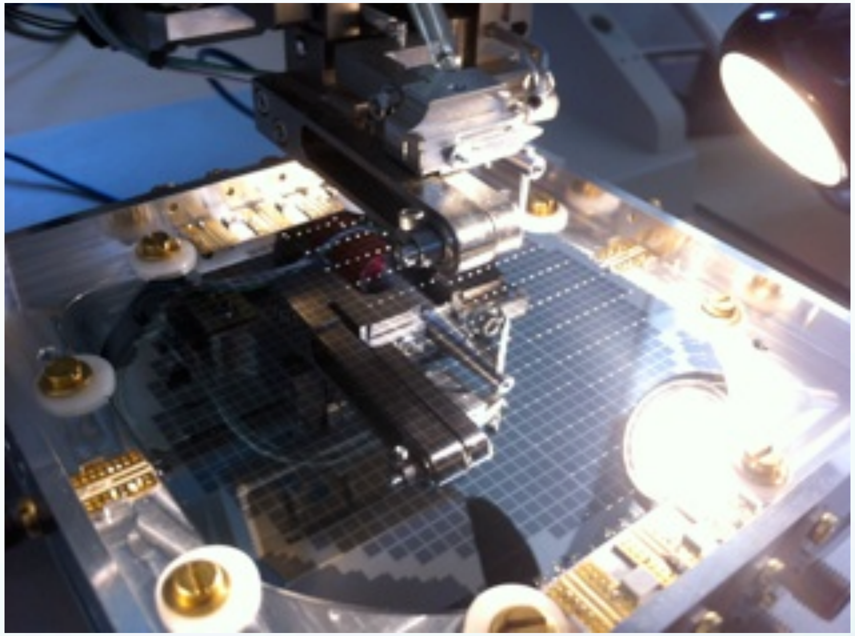
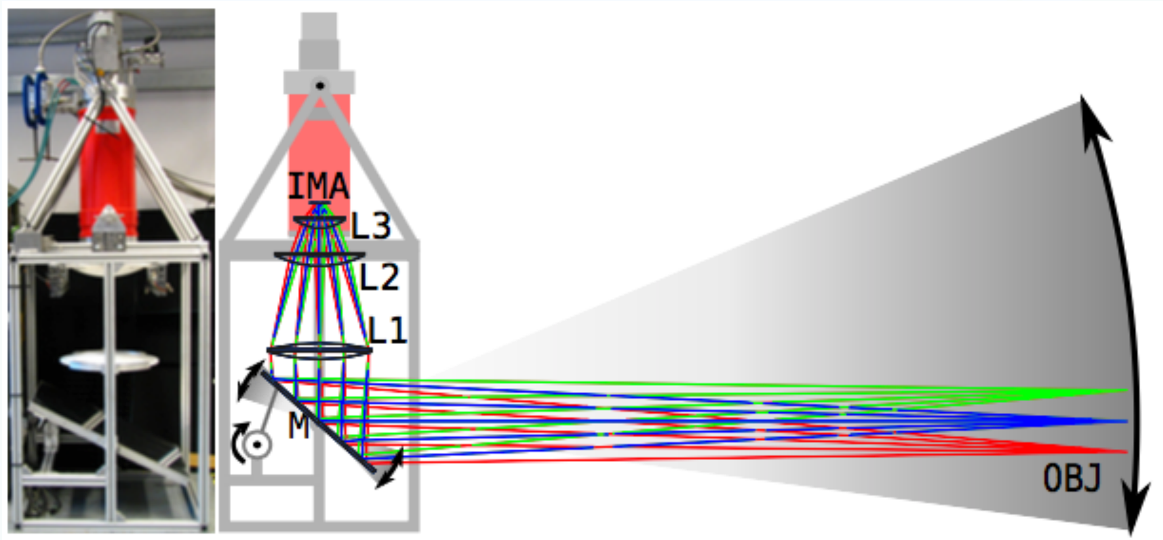
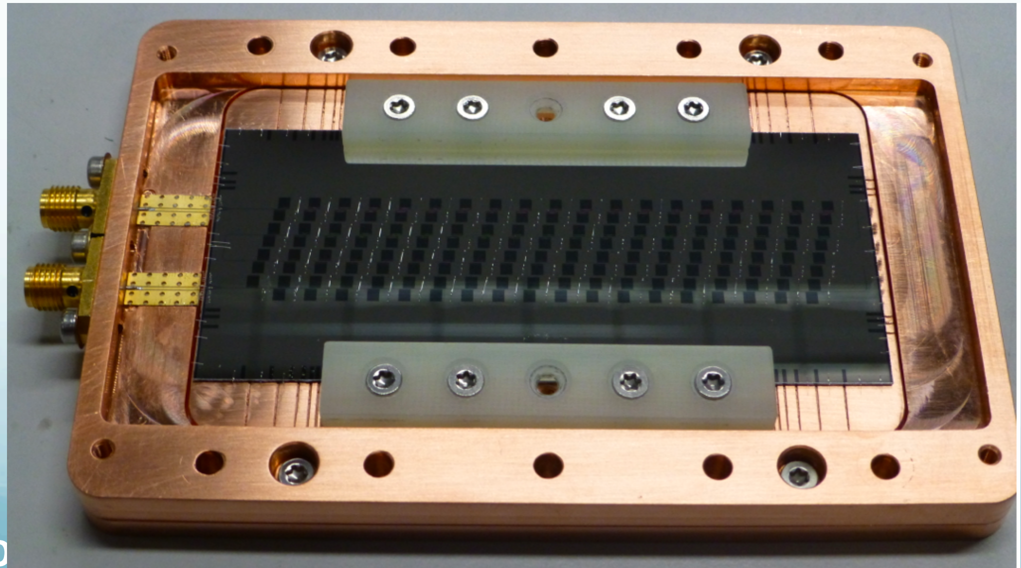


1000 pixels @ 2mm

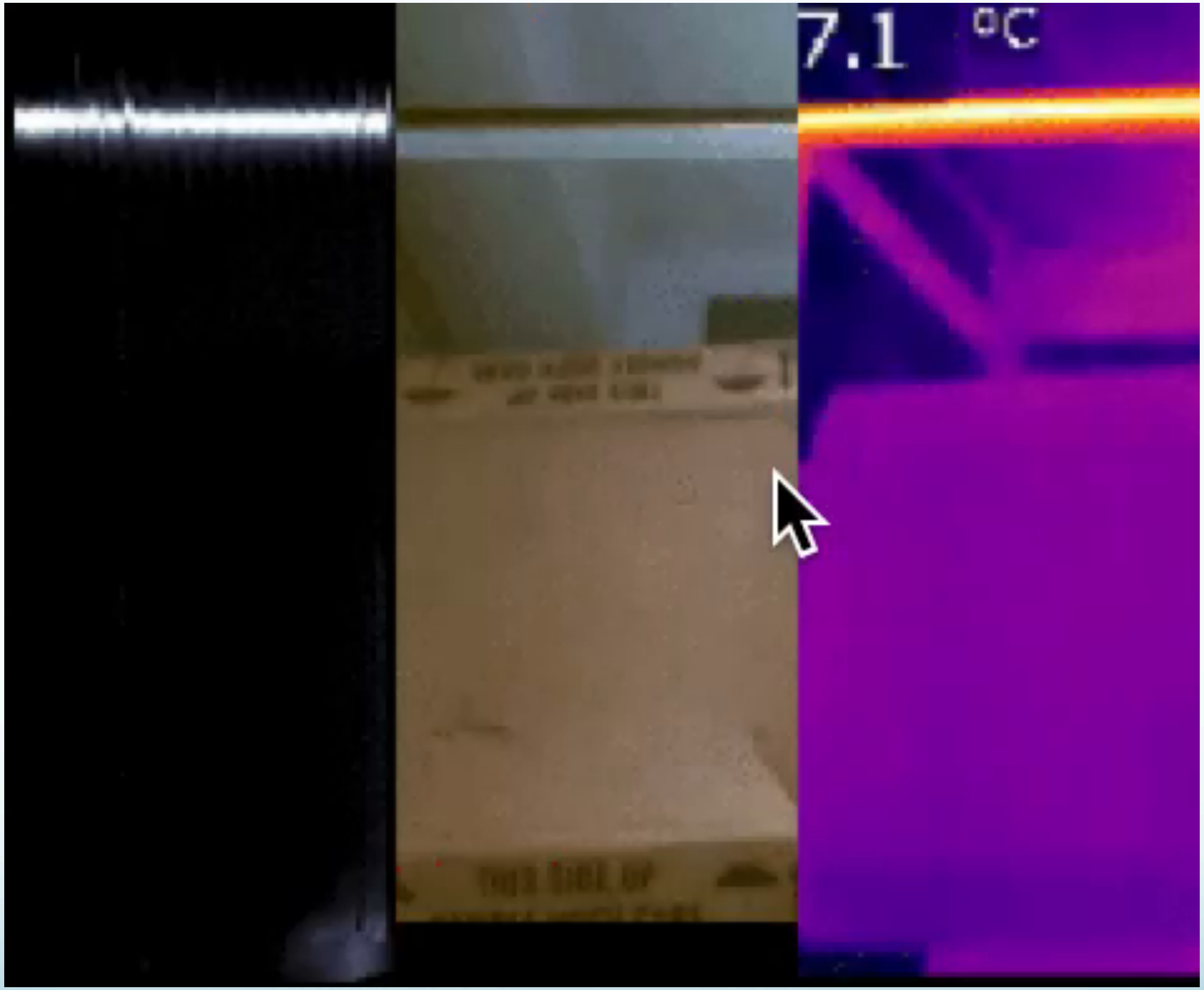
2 x 4000 pixels @ 1mm (2 arrays polarisation sensitive).

KIDcam – A Terrestrial THz imager





KIDcam – A Terrestrial THz imager



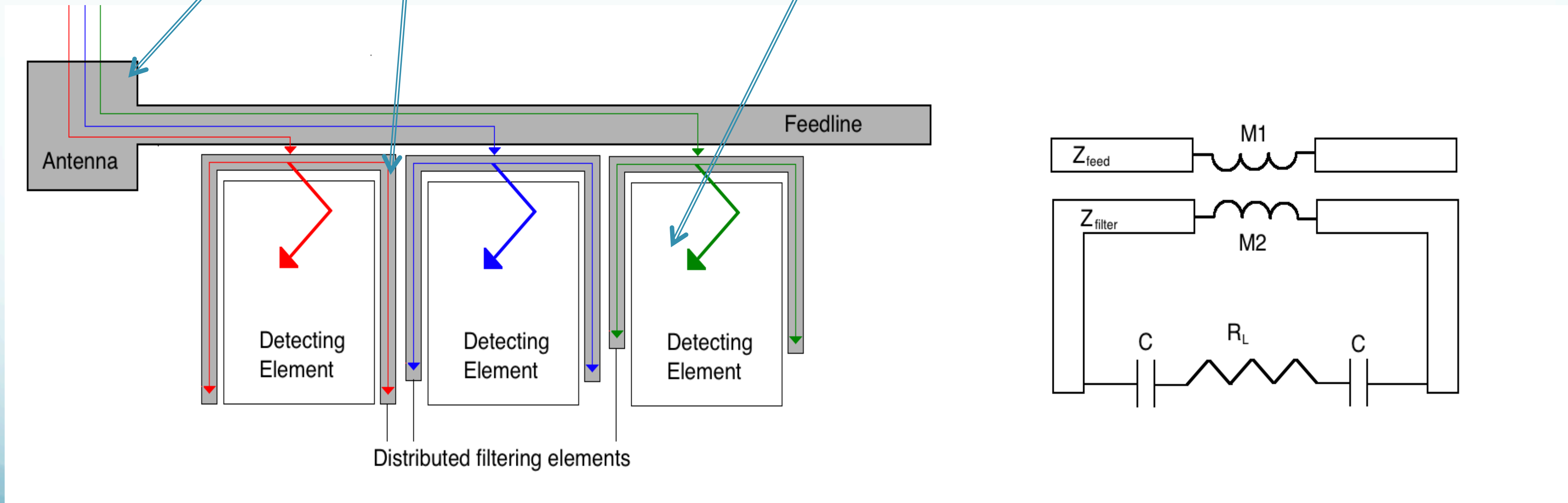
On-Chip Spectrometers

High TC material like Niobium

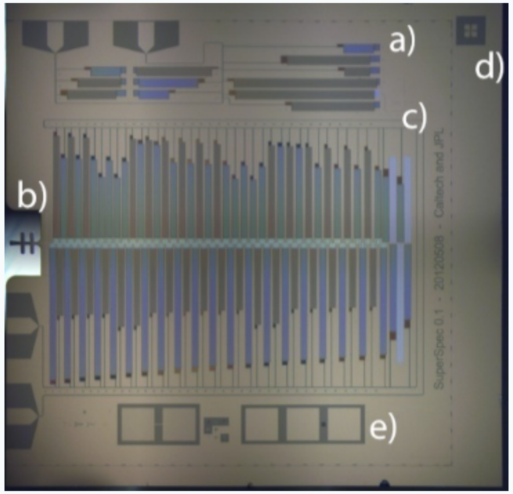
$h\nu < 2\Delta$ $\nu_{cut} \approx 600$ GHz

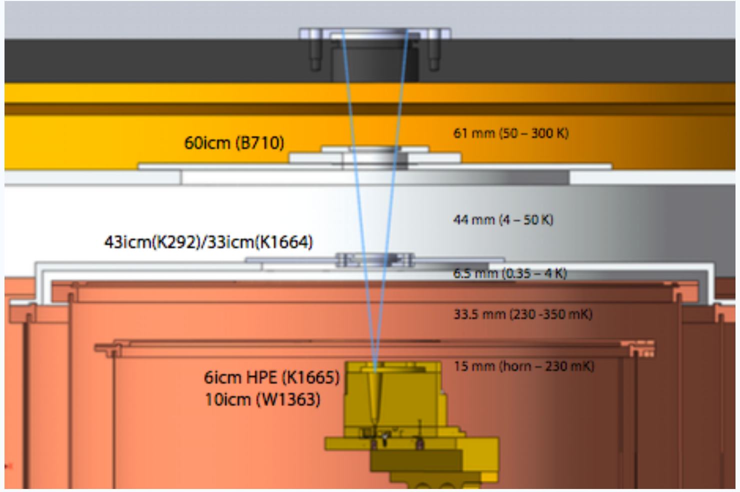
Low TC material like Aluminium

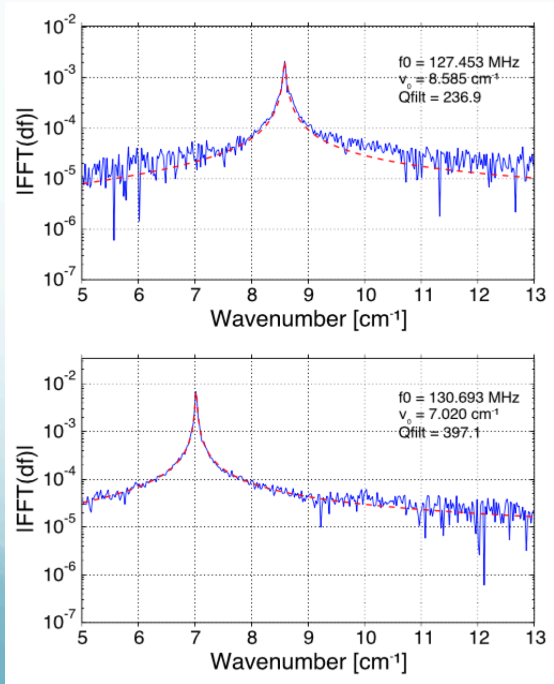
$H\nu > 2\Delta$ $\nu_{cut} \approx 90$ GHz

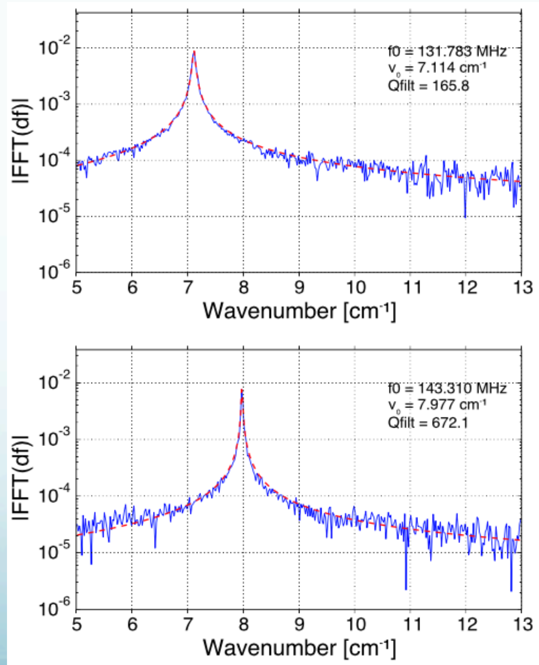


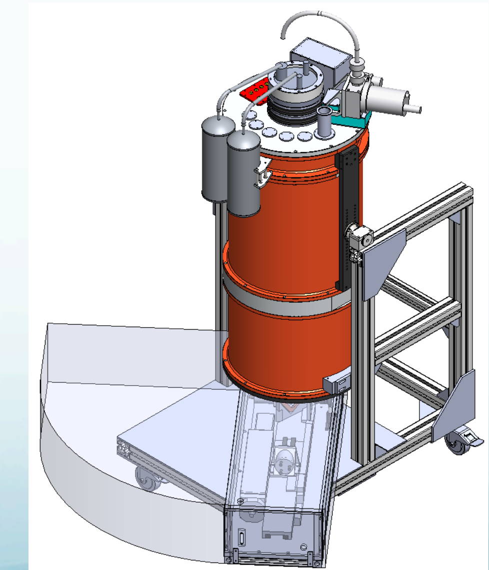
On-Chip Spectrometer Results



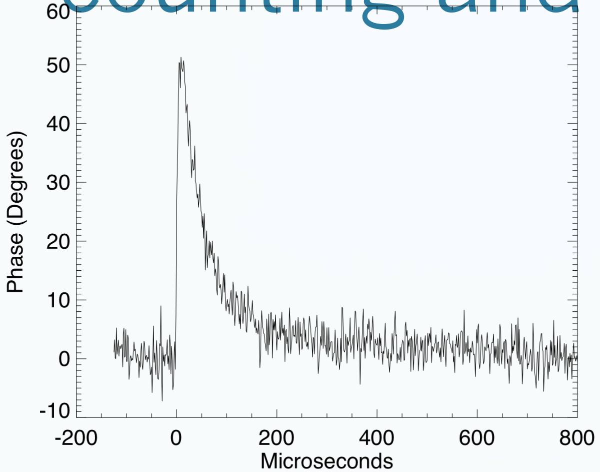


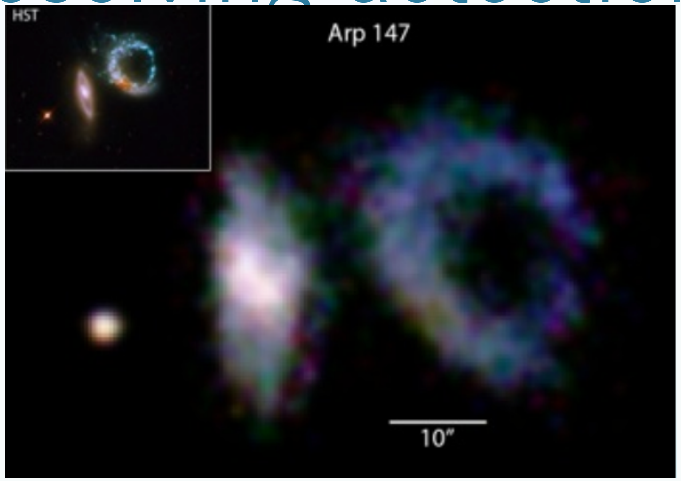


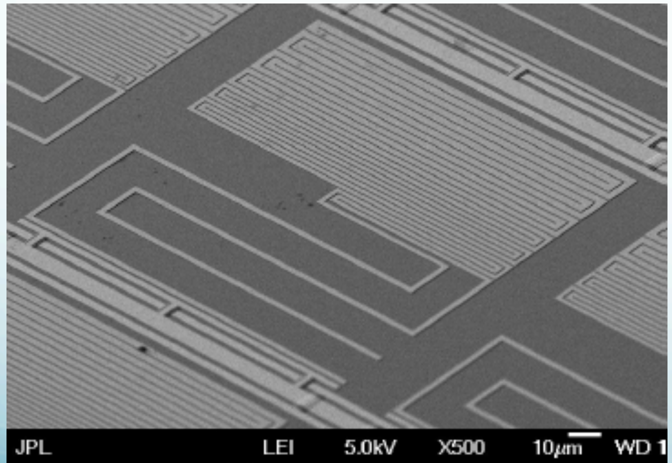


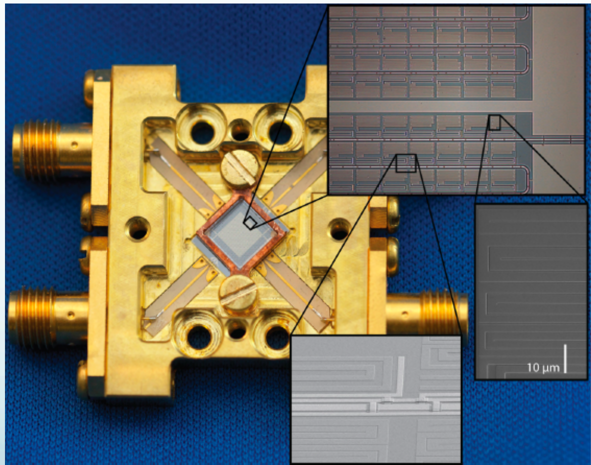


Current applications – Optical photon counting and energy resolving detection









Images courtesy of Ben Mazin, University of Santa Barbara, USA

Conclusion

LEKIDs have been demonstrated to work across a wide range of sensing applications. Some of the key benefits of LEKIDs are:

- **Relatively immune to temperature fluctuations**
- **Very easy to fabricate (single layer process)**
- **Inherently easy to multiplex – MUX ratios of up to 10'000 are achievable**
- **Are sensitive – will meet the photon-noise limit in most cases**
- **Can be used to energy resolve for single photon counting applications.**
- **Are fast – time constants typically of order 10-50 microseconds**

Two-Fluid model of a Superconductor

- Below T_c, the electron population splits into two separate population
  - One of normal electrons known as **Quasi-Particles**
  - One of electrons paired together with a typical binding energy **2Δ** of around 0.4 meV (Aluminium). These paired electrons are commonly known as **Cooper pairs.**

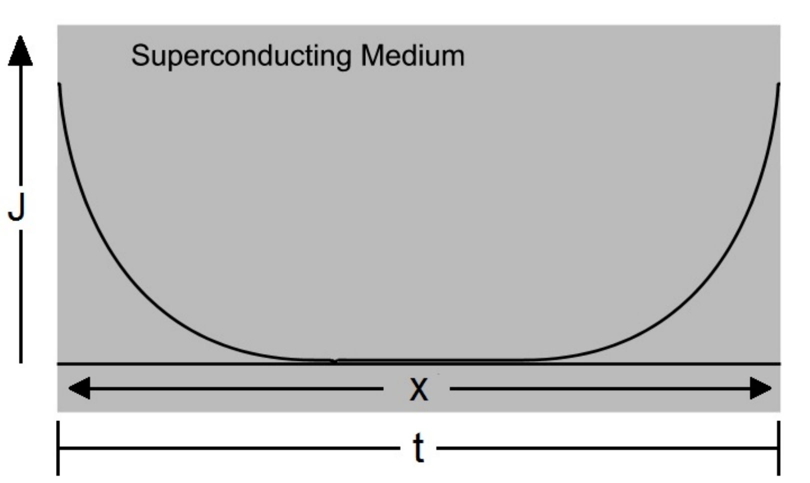
- The **quasi-particle** population acts as a normal metal would do, i.e. is **resistive**. This gives us a **conductance** $\boldsymbol{\sigma_1}$

- The **paired population** are have no resistance but do have an associated reactance known as **Kinetic Inductance / Internal Inductance.** This gives us a **conductance** $\boldsymbol{j\sigma_2}$

- **Absorption of a photon with hυ> 2Δ breaks Copper pairs and alters these populations.**

Internal Inductance for practical film thicknesses

Quite often we are working between the limits of t << λ_L and t >> λ_L. In this case we need to perform the surface integrals for current over the entire film cross-sectional area and take into account any variations in current density.



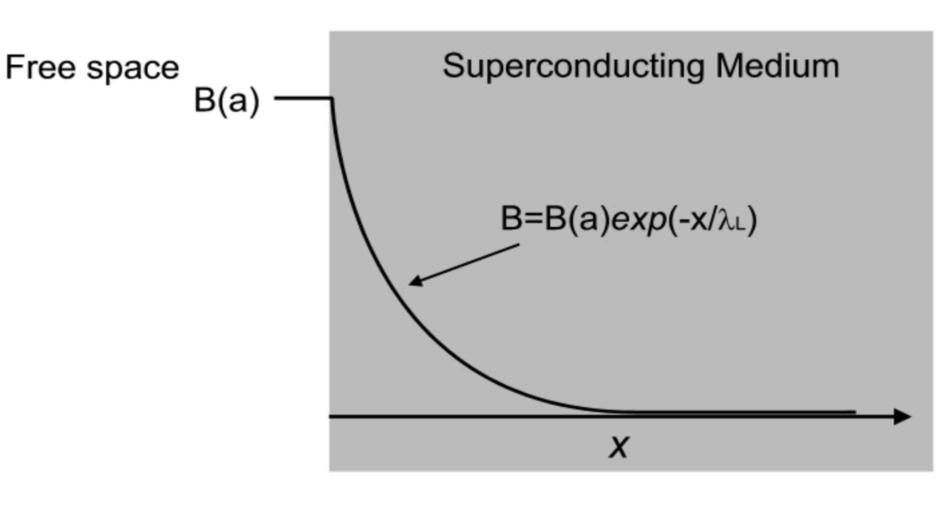
$$L_k = \frac{\mu_0 \lambda_L^2}{4W}\left[\coth\left(\frac{t}{2\lambda_L}\right) + \left(\frac{t}{2\lambda_L}\right)\right]\operatorname{cosec}^2\left(\frac{t}{2\lambda_L}\right)$$

$$L_m = \frac{\mu_0 \lambda_L^2}{4W}\left[\coth\left(\frac{t}{2\lambda_L}\right) - \left(\frac{t}{2\lambda_L}\right)\right]\operatorname{cosec}^2\left(\frac{t}{2\lambda_L}\right)$$

$$\lambda_\mathrm{L} = \sqrt{\frac{m}{\mu_0 n_s e^2}}$$

$$L_{int} = L_k + L_m = \frac{\mu_0 \lambda_L}{2}\coth\left(\frac{t}{2\lambda_L}\right)$$

The London penetration depth



For a non-scattering electron volume

$$\dot{\mathbf{B}}(x)=\dot{\mathbf{B}}(s)exp\left(\frac{-x}{\sqrt{m/\mu_0 n_s e^2}}\right)$$

For a **superconducting** electron volume

$$\mathbf{B}(x)=\mathbf{B}(s)exp\left(\frac{-x}{\sqrt{m/\mu_0 n_s e^2}}\right)$$

Applying Maxwell's equations to a perfect conductor displays diamagnitism of AC magnetic fields.

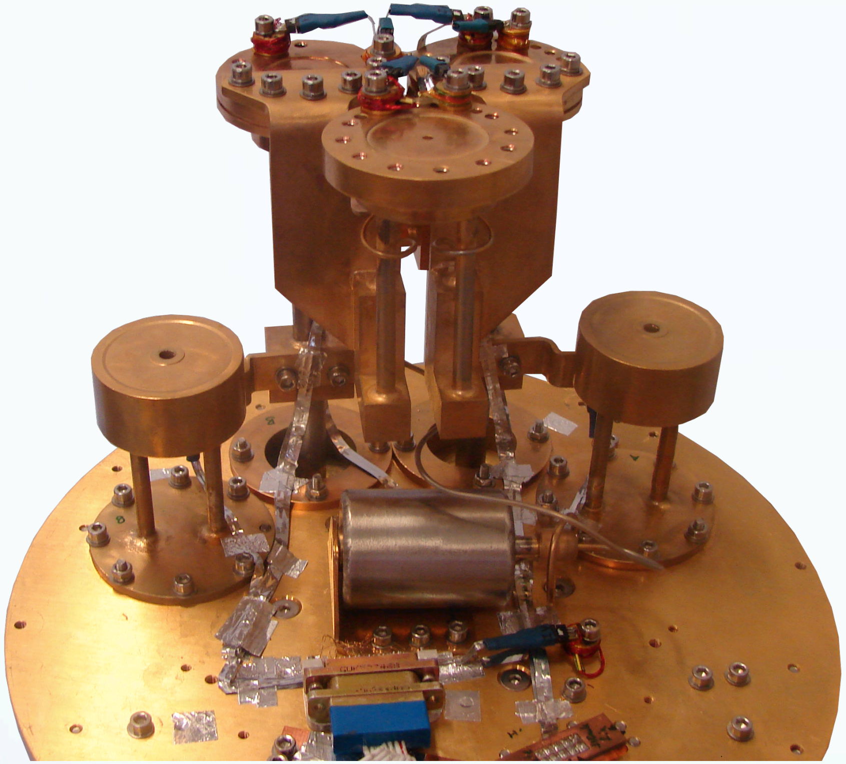
London and London suggested a set of constitutive conditions to Maxwell's equations so that both DC and AC fields as expelled from the bulk of a superconductor.

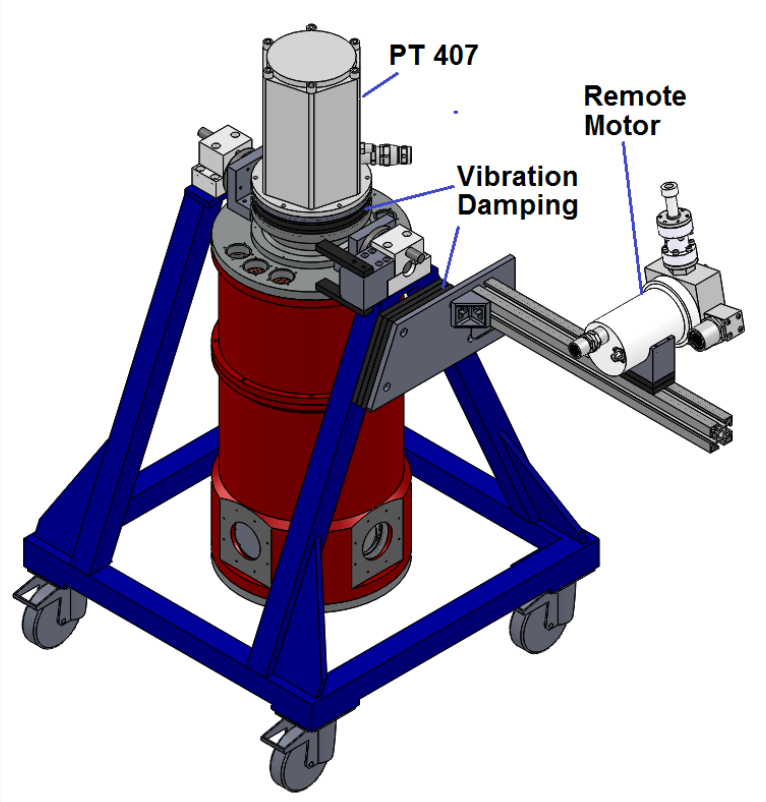
The field decays to 1/e of its value at the surface within the London penetration depth λ_L.

$$\lambda_L = \sqrt{\frac{m}{\mu_0 n_s e^2}}$$

The London Penetration depth

Is a commercial sub-K system viable?





- **Modern pulse tube systems now cryogen free and push button operation.**
- **Closed cycle systems can be automated and continuous. No user input necessary.**